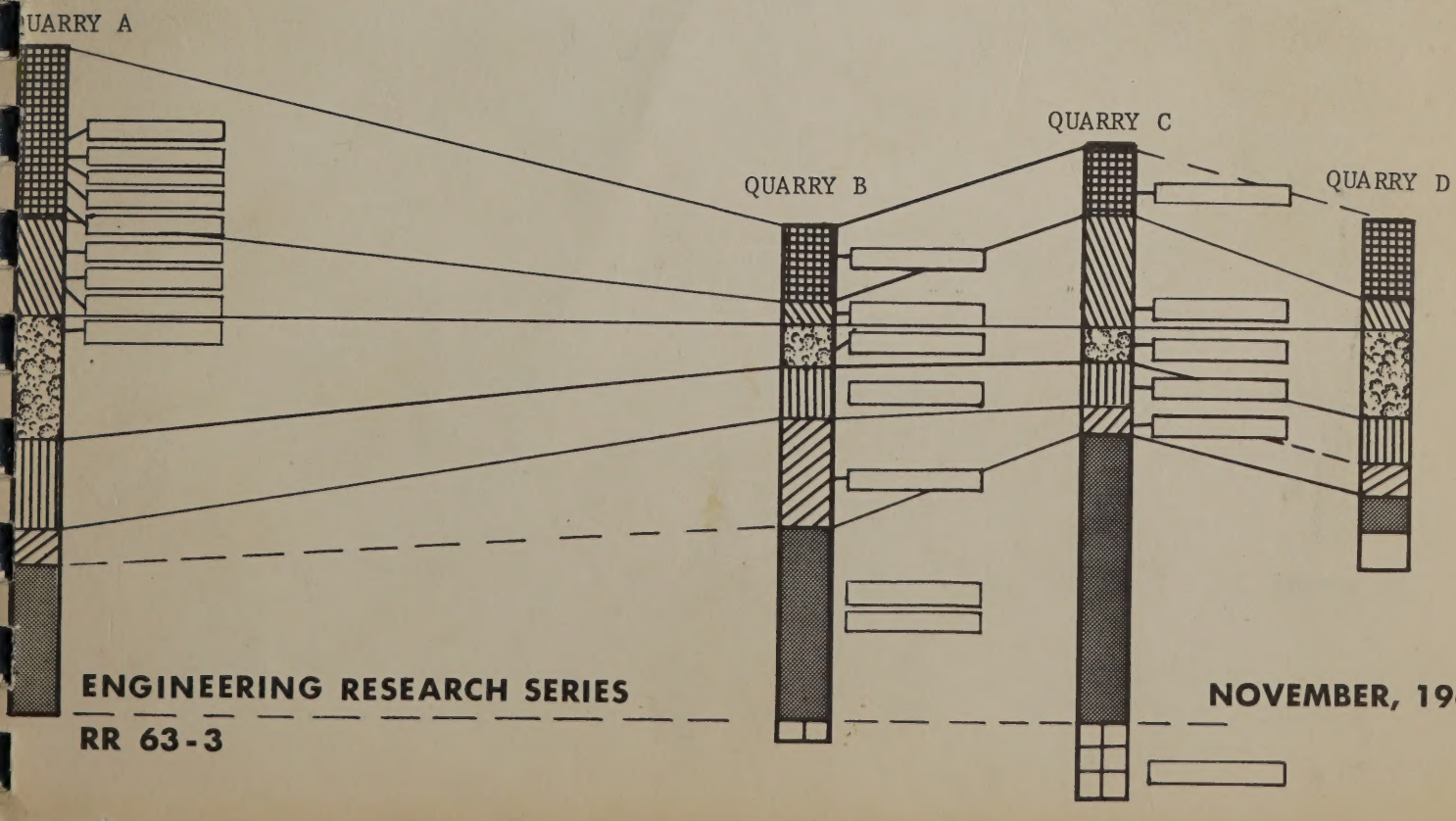
# CHARACTERISTICS OF VARIOUS AGGREGATE PRODUCING BEDROCK FORMATIONS IN NEW YORK STATE

## PHYSICAL RESEARCH PROJECT NO. 4

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# CHARACTERISTICS OF VARIOUS AGGREGATE PRODUCING BEDROCK FORMATIONS IN NEW YORK STATE

Phase 3
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"Acceptability Tests for Coarse Aggregates"

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ABSTRACT

Evaluating the suitability of stone aggregates for use in concrete can entail many problems. This is especially true for public works agencies which must approve new sources of material to keep abreast of the steadily increasing volume of highway construction. Such sources may represent undeveloped areas of existing quarries or new quarries operating in rock formations which have been supplying acceptable stone. Problems arise from the fact that the chemical properties and physical characteristics of rock formations can vary appreciably, even within single lithologic units. Consequently, aggregates from seemingly identical sources sometimes exhibit marked differences in the properties which determine their suitability for construction.

In New York State, the supply of stone is virtually inexhaustible. However, evaluation of aggregate quality is complicated by the wide variety of rock types encountered. At present, approximately 80 quarries operate in at least 6 limestone formations, 5 dolomite formations, 2 sandstone formations, and an assortment of crystalline rocks. Some of these formational units extend laterally as much as 200 miles within the state boundaries. It has been necessary, therefore, to enforce rigid acceptance requirements in the form of laboratory soundness tests. While these tests prevent excessive variations in the quality of aggregate

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supplied for public works construction, a straightforward interpretation of the results is not always possible. For example, an aggregate may pass one soundness test but fail another. This apparent conflict can be explained, in part, by the fact that the same properties of an aggregate are not measured by all the tests. This also suggests that small variations in some characteristics of aggregate-producing rock formations may significantly affect the uniformity of aggregate quality.

In view of the diverse geologic rock formations in New York, the Department of Public Works has initiated an extensive investigation of various aggregate-producing formations in the state, and the laboratory tests by which their acceptability is determined. The magnitude of this undertaking required the assistance of qualified geologists who are familiar with the conditions in New York, and who are experienced in relating geology to the performance of construction materials. Accordingly, a contract was negotiated with Rensselaer Polytechnic Institute, Troy, New York, covering a large portion of the work. The studies have been carried out under the supervision of Dr. James R. Dunn, Department of Geology, who also prepared this report.

The carbonate rock formations discussed in this report comprise a group of dolomites, limestones, and argillaceous (clayey) dolomitic-limestones occurring in western and central New York which have generally exhibited a consistent pattern of performance in

laboratory soundness tests. Collectively, they represent a substantial portion of the currently approved sources of aggregate in the state. In addition, a sandstone formation studied by Professor Dunn with funds provided by a group of private companies is included with their permission. Primarily, the investigation has attempted to systematically sample and test each formation to the extent that variations in chemical properties and physical characteristics can be established within reasonable limits. The second objective has been to correlate the identifying properties of each formation with the results of laboratory soundness tests and field performance.

Each of 79 fifty-pound block samples of carbonate rocks obtained from quarry faces were subjected to a comprehensive series of tests including chemical, normative (theoretical mineralogic analysis), insoluble residue, chemical reactivity (dedolomitization), X-ray, and petrographic analyses. In addition, all samples were tested for specific gravity, water absorption, freeze-thaw, Deval abrasion, sulfate soundness, and compressional wave velocities. Selected specimens were also tested in different orientations for shear wave velocities and thermal expansion. The samples of sandstone were subjected to limited testing.

As a result of this investigation, each of the formational units studied has been delineated and its characteristics described in detail. This has been accomplished by stratigraphic profiles

and analyses of test results. Moreover, several important conclusions regarding the relatinnship between aggregate properties and soundness tests, and a theoretical discussion of freeze-thaw soundness are presented. The interpretation of the conclusions, which are too numerous to review here, is given in the following:

1) The formations investigated in central and western New York vary from sandy to clay-rich carbonate rocks which cover a wide range of chemical and mineralogic types from almost 100% calcite to 100% dolomite. Differences in the composition of contiguous lithologic units are generally more pronounced than the variations within each unit.

2) The results of standard soundness tests do not have a simple correlation with other tests or with the physical and chemical properties of the rock samples. It is not possible, therefore, to establish the acceptability of a source merely on the basis of lithologic classification.

3) Critical quantities of clays, principally potash deficient illite, and the availability of water determined by pore size characteristics, are probably the most significant factors which influence the performance of the carbonate aggregates in sulfate soundness and freeze-thaw tests.

4) Except for two isolated cases, none of the rocks tested exhibited excessive expansion associated with chemical reactivity (dedolomitization).

5) Of the standard tests for determining the soundness of aggregate, the magnesium sulfate and freeze-thaw tests are the most reliable. This is in agreement with the deletion of the sodium sulfate test from the January 2, 1963 New York State Department of Public Works Specifications.

6) Aggregate service records cited in this report suggest that the current freeze-thaw requirements for concrete aggregates could be relaxed without affecting the quality of concrete.

7) Theoretical considerations of freeze-thaw phenomena and laboratory studies indicate that water absorption and vacuum drying tests may be good indicators of freeze-thaw performance. Such tests should be conducted on a wide variety of carbonate rocks for an extended period before the results can be considered conclusive.

Based on these studies, the following recommendations are considered appropriate:

1) The possibility of performing laboratory acceptance tests on cored samples of each layer or lithologic unit should be considered in order to overcome the masking effect of "averaged samples" from quarry stockpiles. If practicable, quarrying operations could then be conducted so as to eliminate or minimize the influence of questionable zones.

2) The current freeze-thaw requirements for concrete aggregates should be reviewed in the light of all available service records of exposed concrete and acceptance test results.

3) The water absorption and vacuum drying tests described in this report should be continued on all samples, along with the standard acceptance tests. If proven reliable, the simplicity of these tests may result in significant savings in time and effort by elimination of the equivalent time-consuming standard tests.

ACKNOWLEDGEMENTS

The author would like to express appreciation to those people and agencies without whose cooperation this research would not have been possible.

Financing of the research on carbonate rocks was by the New York State Department of Public Works in cooperation with the United States Department of Commerce, Bureau of Public Roads, under the State-Federal Physical Research Program. The research on the Catskill graywackes was sponsored by Cooney Brothers Inc., John Arborio Inc., Sullivan Highway Products Corporation, and Corbisello Quarries Inc. Their contributions and cooperation are gratefully acknowledged. The help of Mr. Frank Cooney was particularly valuable in obtaining research funds from the various companies.

The research was conducted largely at Rensselaer Polytechnic Institute, Department of Geology. Most of the sulfate soundness tests and all of the freeze-thaw tests and chemical analyses were conducted in the Albany laboratories of the New York State Department of Public Works by State personnel.

In particular, the cooperation and help of the following people in the New York State Department of Public Works is gratefully acknowledged: George McAlpin, Harry McLean, Paul Bird, Malcolm Graham, Ignatius Rizzuto, and William Chamberlin.

The author would also like to express appreciation to the technical personnel at Rensselaer Polytechnic Institute and the New York State Department of Public Works who assisted in various phases of technical work.

The author would like to express appreciation to the following Rensselaer graduate students who were responsible for carrying on much of the research: Larry Cline, John Kaufman, Richard LaBrake, Mahdi Mohammed and Michael Ozol were involved in the carbonate and chert work. Ronald Senechal did the Catskill graywacke work.

Professor Samuel Katz of the Geology Department of Rensselaer set up the sonic velocity equipment and contributed much valuable time and advice to the research on the sonic velocities. Professor D. S. Miller, Rensselaer, is to be thanked for taking time to critically read and review much of the manuscript. He also directed the research on the Catskill graywackes on which several important sections of this report are based. Thermal expansion determinations were made by Professor D. T. Smith at Rensselaer.

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# INTRODUCTION TO PARTS I, II, III

For the years 1960 through 1963 the Geology Department at Rensselaer Polytechnic Institute has been conducting research on various rock types which occur in New York State to determine characteristics which might have a bearing on their use as aggregate. Rocks which were studied include nearly all lithologic types of the Lockport formation (dolomite) and Manlius formation (limestone). In addition, typical lithologies of Catskill graywackes, Onondaga formation (limestone), Pamelia formation (limestone and dolomite), Cobleskill formation (dolomitic limestone) and Rondout formation (dolomite) were studied. Funds for the research on carbonate rocks were obtained through the New York State Department of Public Works. Funds for the graywacke research were obtained from four quarry companies (see acknowledgments).

The purpose of Part I is to summarize and make the more obvious interpretations of the physical and chemical data. The purpose of Part II is to summarize all pertinent geologic data, such as sample locations, stratigraphy and petrography and to correlate Part I stratigraphically. The purposes of Part III are to cross correlate Parts I and II; to analyze theoretically freeze-thaw action; and to suggest lines of future research which might prove fruitful in assessing in the laboratory the ability of a rock to withstand freezing and thawing in concrete under field conditions.

The intent of this report is to summarize critical physico-chemical data for various rocks in New York, to ask questions, and, hopefully, to act as a guide to future lines of research and testing. The ideas expressed here are not official views of Rensselaer Polytechnic Institute, or the New York State Department of Public Works, or the crushed stone industry but those of the author.

# PART I

## SUMMARY OF TESTS AND TESTING PROCEDURES

## INTRODUCTORY STATEMENT, PART I

A primary consideration in all rock testing is the proper selection of samples. The problem of sampling is complex and demands a knowledge of the distribution of the characteristics of a rock before it can be done properly. Yet if the research itself is to determine the characteristics of the rocks, a paradox seems to exist in that the best time to sample would be after, not before the research. Therefore, sampling must always be a compromise between economy, time and anticipated utilization of results.

The sampling procedure which was finally decided upon for the work with carbonate rocks is as follows: (1) Quarry faces were logged in enough detail so that all megascopically distinct rock types were determined. (2) The distinct types were noted by position (distance from quarry floor or other reference planes) and their thicknesses determined. (3) A "typical" block of rock of about 50 pounds was selected from each unit and all testing was done on that block.

Test blocks of similar size were selected for the graywacke research, but they were not located stratigraphically nor were the rock faces logged in detail. It is believed that because of the lack of lateral continuity of the graywackes, detailed logging would be useless.

The advantages of such block sampling are: (1) Correlation between various measured characteristics is done with more assurance, and (2) the sampling and testing is relatively inexpensive. The major disadvantage is that any block selected must be somewhat different than any other such block and the magnitude of this difference is not known. However, where a unit was sampled more than once, the differences between tests on the duplicated samples are generally far less than the differences between units. The potential chemical continuity of rock layers is well demonstrated in the Helderberg limestones in the Hudson Valley where it was shown that over a mile along strike the chemical composition of the rock units varied less than the analytical error in the chemical analyses (Dunn, 1961).

The data which were determined for most samples were:

1. Locations: Aerial and stratigraphic position.
2. Stratigraphic and petrographic data: Hand specimen and thin section descriptions, logging of cores.
3. Chemical and mineralogic characteristics: Chemical analyses, chemical reactivity with portland cement, insoluble residue quantities, X-ray analysis of clay fractions, normative analyses (calculated mineralogy from chemical analyses).
4. Physical characteristics: Specific gravity (5 methods), porosities, water absorptions, pore size distribution, thermal expansions, compressional and shear wave velocities, wetting and drying, sodium sulfate and magnesium sulfate soundness, freeze-thaw and modified Deval abrasion tests*, rate of drying in vacuum.

*According to NYSDPW Specifications.

All of the above characteristics were not determined for all samples because of the different purposes of various aspects of the research. Table I-1 is a summary of the number of samples which were tested in each way. Sample locations are shown on Plate I-1.

TABLE I - 1

Data Obtained - Carbonate Rocks

| Chemical Data | Approx. No. | Comments |
|---|---|---|
| Chemical analysis | 80 | |
| Normative analysis | 80 | |
| X-ray, clays | 80 | |
| Insoluble residue | 80 | |
| Dedolomitization | 80 | |
| Dedolomitization, ph | 80 | |
| X-ray, dedolomitized specimens | 3 | |
| **Petrographic Data** | | |
| Description | | All formations |
| Photomicrographs | | Typical units |
| **Physical Data** | | |
| Sp.g. bulk dry | 79 | |
| Sp.g. bulk saturated | 79 | |
| Sp.g. apparent | 79 | |
| Sp.g. true | 79 | |
| Porosity | 80 | |
| Compressional wave velocity | 79 | |
| Shear wave velocity | 20 | |

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| **Petrographic Data** | | |
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| Porosity | 80 | |
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| Shear wave velocity | 20 | |

# Plate I-1
# SAMPLE LOCATIONS

(Base Map - State of New York
D.P.W. Quarry Locations,
Research Report 61-3)

Plate I-1
SAMPLE LOCATIONS

Page
6a

| Physical Data | Number | Comments |
|---|---|---|
| Poisson's ratio | 20 | |
| Thermal expansion | 24 | |
| $MgSO_4$ soundness | 79 | |
| $Na_2SO_4$ soundness | 79 | |
| Deval abrasion | 75 | |
| Water absorption | 79 | |
| Wet dry sensitivity | 10 | |
| Rate of absorption and loss of water | 15 | |
| Service failures checked (partially oral) | 4 | |

Data Obtained - Graywackes

| Chemical Data | Number | Comments |
|---|---|---|
| Chemical analysis | 5 | Remarkable Similarity |
| X-ray, clays | | Typical Samples |
| **Physical Data** | | |
| Water absorption | 34 | 145 hrs. Not included here. |
| Rate of water absorption | 12 | |
| Freeze-thaw | 18 | 9 in duplicate |
| Pore size distribution | 14 | |
| $MgSO_4$ Soundness | 18 | 9 in duplicate (many additional small samples run at RPI, results not included here). |

| Physical Data | Number | Comments |
|---|---|---|
| Reproducibility, $MgSO_4$ test | 2 | |
| Particle shape vs. $MgSO_4$ test | 85 | Mostly non-standard tests. |

## CHEMICAL PROPERTIES

### Introductory Statement

The chemical characteristics of aggregate are directly and indirectly related to soundness and hardness, but the relationship is not always clear. Because of this uncertainty of correlative relationships, the research on chemical characteristics has not been oriented toward any particular aspect of the chemistry but rather toward obtaining all data which could be determined within the temporal and monetary framework of the research. All rocks were analyzed chemically in the laboratories of the N.Y.S.D.P.W. and from this information calculations of theoretical mineralogic compositions were made largely with Fortran analysis on an IBM 1410 Digital Computer at Rensselaer.

Insoluble residues were determined at Rensselaer from fractions of the same samples and were then used as a check for both the normative mineralogy and chemical analyses. The clay mineralogy of all samples were studied with an X-ray diffractometer and related to the normative mineralogies. The whole mass of chemical data was further checked by petrographic work to determine the general reliability of the information. All aspects of the chemistry have been completely checked and are believed to be reasonably internally consistent within the limits of accuracy of the analytical methods employed. The chemical analyses are given in Table A-1.

## Chemical Analyses

All rocks studied in this report were analyzed chemically in the New York State Department of Public Works laboratories in Albany, New York. The tabulation of all chemical analyses on Table A-1 is by geologic formations and members in order of age. No systematic interpretation has been made of the chemical analyses as to internal consistency and accuracy, but no major discrepancies have been found in their relationship to other data. In some cases the analyses added up to more than 100% and some difficulty was encountered by the computer when normative mineralogic calculations were made.

(It should be noted that "insoluble matter" as reported in the chemical analyses is that component of the sample which remains after digestion in HCl and HF. This is not the same as the "insoluble residue" determined at R.P.I. (Table A-2), which is the theoretical HCl acid-insoluble material calculated from the chemical analysis by computer. Insoluble residues were determined for most specimens by actual acid leach at R.P.I., but the data are not included in this paper.)

## Normative Mineralogic Calculations

Clays, free silica, and the nature and ratio of carbonates have an important bearing on the possibility of potentially expansive reactions by the interaction of components of the portland cement and aggregate.

Imbrie and Poldervaart (1959) presented a normative analysis scheme for determining the theoretical mineralogic composition of sedi-

mentary rocks from their chemical composition in a manner similar to that used for igneous rocks. The scheme has shortcomings, as do the igneous normative calculation schemes, but until it has been applied systematically and checked thoroughly, its value cannot be determined. The principal importance to the present project is that it shows, in a rough way, the total clay and free silica contents, the likely types of clay and the calcite-dolomite ratio. However, it must be stressed that the presence of a clay in the normative analysis does not necessarily mean the particular clay is present. Verification should come from other sources, such as X-ray, staining or differential thermal analysis techniques, as subsequently discussed.

The normative calculation scheme is long and tedious. Initially work was done on a two page form with appropriate blanks for the calculation (see appendix B-1, pg. 181 ). The work was very slow and the possibility of error was great. Most calculations were finally run on a computer in the Rensselaer computer laboratory. The principal disadvantage to the computer is that if a chemical analysis has internal inconsistencies, the computer is unable to "see" them. Where such minor inconsistencies occurred, the normative analyses were calculated by various personnel.

The theoretical mineralogy is summarized in Table A-2, p. 161.

X-ray Analysis of Clay Components

Papers proposing schemes for separation and identification of clays are found throughout the geologic literature (for review see Ostrom, 1961).

The major problem in carbonate rocks is to obtain a suitable amount of fresh clay unaltered by acid. Detailed analysis, using large quantities of fresh clay, would be necessary to clarify the proportions and kinds of clays present in the samples tested. Therefore, remarks in the present paper as to the nature of clays, either from X-ray study or norm analysis, must be tentative.

The clay mineral components of all limestones were studied with X-ray diffraction techniques using a General Electric XRD 55 X-ray Diffractometer. Clays were separated from the carbonate matrix with diluted hydrochloric acid, collected on 1.8" X 1.0" glass slides, dried and subjected to diffractometer analysis. Identification of clays was performed according to a scheme proposed by Warshaw and Roy (1961).

Three groups of diffraction peaks were represented, 7Å, 10Å, and 14Å. Because of the tendency of clay minerals to repeat their structural layers, the presence of particular peaks is not necessarily indicative of a particular clay mineral. However, a combination of peaks increases the probability of the presence of certain clay minerals. The major value of the X-ray diffraction work is that it enables us to compare the clay fractions of various rocks eventhough, with the present state of knowledge, it is not always certain which clays they are.

The results of X-ray analyses are given in Table A-3, p.165.

The 10Å peaks indicated the probable presence of illite. On the basis of calculations from chemical analyses and lateral shifts in the position of the 10Å peak on wetting and on baking, Kaufman (1963) concluded that the illite in the freeze-thaw sensitive rocks was expansive and probably potash-poor. Kaufman also verified the presence of kaolin and chlorite in many of the dolomitic rocks discussed in this report by X-ray and electron microscope technique.

It must be stressed that other clays may be present and important, but not identifiable with the techniques used and in the quantities which may exist.

Insoluble Residue

Three methods were used to determine "insoluble residue". The "insoluble matter" which is included in the chemical analyses determined by the N.Y.S.D.P.W. is that component of the analyzed sample which is insoluble in the reagents which were used in digestion for the analytical scheme. The "insoluble residue" with the normative analyses is the total of the percents of $H_2O$, $SiO_2$, $Fe_2O_3$, $TiO_2$ and "insoluble matter" from the chemical analyses. "Insoluble residues" were also determined at R.P.I. for most samples by acid leach, but the results are not included in this report.

Of the three values the insoluble matter is always the smallest, in the vicinity of 1%. The insoluble residue on the normative tables is usually 1-2% less than the insoluble residue which was determined by actual acid leaching at Rensselaer. The insoluble residue figures may be about the same as total quartz, clay, minor constituents and insoluble matter or the figures may be radically different. Where discrepancies exist, the normative figures are in error. (Error in the normative scheme occurs largely because the total clay is a function of the $K_2O$ content, not the $Al_2O_3$ content. Enough $Al_2O_3$ is considered to be present to combine with $K_2O$ to form potash clays, whether or not enough $Al_2O_3$ actually exists.)

High insoluble residues are sometimes considered to be an indication of unsound aggregate, but if the insoluble residue is mostly quartz or feldspar, deleterious effects are unlikely. If the insoluble residue is largely clay, the chances of deleterious reactions in concrete are increased. However, the presence of large amounts of clay is not necessarily harmful in aggregate. The species of clay and the accessibility of moisture to clay are probably more critical factors. In dolomites, clays are generally likely to be more accessible to water, because dolomite crystallization tends to eject foreign materials from crystals to crystal boundaries. Thus the petrographic characteristics of the rock become critical in interpretation of potential unsoundness. For a more complete explanation see Part III.

Dedolomitization

All of the completely studied carbonate rock specimens were subjected to the dedolomitization test used by Hadley (1961). Also 12 samples of the Theresa formation (Beekmantown) were tested, but their stratigraphy is unknown. Cores ½" in diameter with tapered ends were soaked in 1 N NaOH solution and length measurements made at regular periods with a micrometer to an accuracy of 0.0001 inch. For details of procedures see appendix B6, pg.195 .

Two samples - a Beekmantown dolomite (Theresa formation) from northern New York and a specimen of Pamelia dolomite (P-M-3) from

Lowville showed deleterious expansion (both 1.3% at the end of 8 weeks). It is assumed that these rocks would react deleteriously in concrete containing high-alkali cement. No other specimens had expansions which were more than 0.01%, including other samples of Beekmantown and Pamelia.

The theoretical dedolomitization reaction is:

dolomite brucite calcite

$$CaMg(CO_3)_2 + 2NaOH = Mg(OH)_2 + CaCO_3 + Na_2CO_3$$

The reaction is apparently favored by high clay contents and a calcite to dolomite ratio of 1:1 (Hadley, 1961). However knowledge of this reaction is so recent that it is felt that a full interpretation is still forthcoming. The calcite-dolomite ratio of the expansive Beekmantown, for instance, in this series did not fit the ideal 1:1 ratio of calcite to dolomite or the high clay content. Expansion occurs in the change of dolomite to brucite plus calcite and is the theoretical cause of the expansion of cores. However, it is entirely possible that significant dedolomitization could occur which might not be reflected in expansion of the bar if the rock has sufficient pore space to absorb the reactant products. Blocked pores could later cause freeze-thaw deterioration, because water might not be able to move ahead of the freeze-front. (See Part III).

The presence of brucite has not been verified by X-ray in the present project. The possibility of another reaction "as the result of or in association with the dedolomitization" (Feldman and Sereda, 1961) (or in lieu of) should be considered. Refer to Table A-4.

## PHYSICAL PROPERTIES

### Introductory Statement

Specific gravities, absorptions, compressional and shear wave velocities, thermal expansions, soundness tests, wet-dry sensitivity, and rates of water absorption and loss are summarized in this section. Possible correlations between data are suggested and when possible theoretically analyzed. Soundness tests are not fully interpreted here because they are summarized and theoretically interpreted in Part III.

### Specific Gravity and Absorption

Determinations of specific gravity were made in several ways for most test specimens and for different purposes. All methods were not used on all specimens because of inherent unreliability of some of the techniques which showed up over a period of time.

The types of specific gravity which were determined are:

Bulk specific gravity (oven dry) defined as: $\frac{A}{B-C}$

Bulk specific gravity (saturated, surface dry) defined as: $\frac{B}{B-C}$

Apparent specific gravity defined as: $\frac{A}{A-C}$

Where A = weight of the oven-dry sample in air,

B = weight of saturated surface-dry sample in air,

C = weight of saturated sample in water

From the above the water absorption can be determined: Percent absorption = $\frac{B-A}{A} \times 100$

The true specific gravity was determined with a pycnometer on 150 to 200 mesh material for most specimens.

An alternate method of determining bulk specific gravity was used when pore size determination runs were made with a Ruska Permeameter. The volume was determined by measuring the amount of mercury displaced by the specimen and the weight determined on an oven dry basis.

Through use of the pycnometer determination of specific gravity ($\rho_B$) and the bulk, oven dry method ($\rho_G$) with the permeameter, a figure for porosity could be determined: $P=1-\frac{\rho_B}{\rho_G}$

The reproducibility of both of the above methods was very high, $\pm$ 0.007.

However, because of limitations of time and the necessity of making determinations on many samples in the permeameter in order to establish the bulk specific gravity in this manner, the method was discontinued as a standard procedure.

All specific gravities which were measured are included in Table A-5, pg.168, together with the results of thermal expansion and sonic velocity tests to be discussed. Soundness data, water absorptions and porosities are recorded in Table A-6, pg.172 for the carbonate rocks and Table A-7, pg.175 for the graywackes.

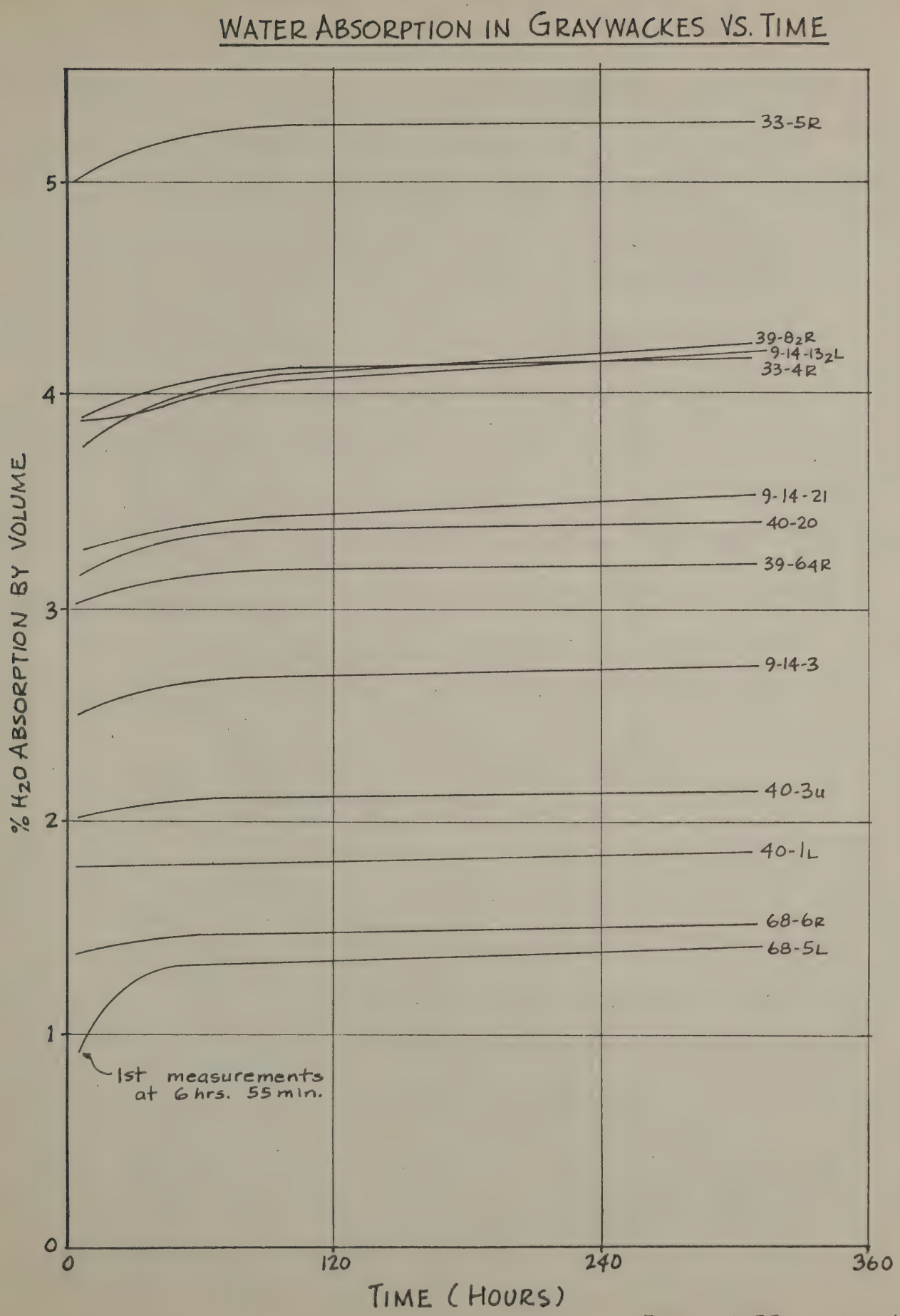
Generally speaking the highest specific gravities are found in the dolomitic rocks because the mineral dolomite has the highest specific gravity of the common minerals in carbonate rocks (2.8 - 2.9). Calcite has a specific gravity of 2.71 and quartz 2.65 to 2.66. The specific gravities of clays are in same range as the above minerals, but generally, abundant clay seems to reduce the specific gravities slightly from those which would be anticipated from the mixture of carbonates and silica alone.

Rate of Water Absorption and Loss

The volume of water absorbed was plotted against time for 12 Catskill graywackes for 0 to 300 hours by Miller and Senechal (1962), see Figure I-1. Most of the water was absorbed within the first few hours for all specimens, with water absorbed up to 300 hours in all specimens but at greatly decreased rates.

Rates of water absorption were also determined for 12 carbonate rocks and one chert. The specimens selected were examples of wet-dry sensitive dolomites, a porous, reactive chert, and several porous, low-clay dolomites as standards. From 5 to 10 pieces weighing a total of about 400 to 800 grams were soaked in tap water at atmospheric pressure and removed, surface dried and weighed at specified intervals as indicated on Figure I-2 . The specimens were then soaked in water in a vacuum for another 2 to 3 hours to determine the probable saturation percentage. The same saturated specimens were then placed in a vacuum at room temperature ($70^{\circ}F$) and removed and weighed at regular intervals.

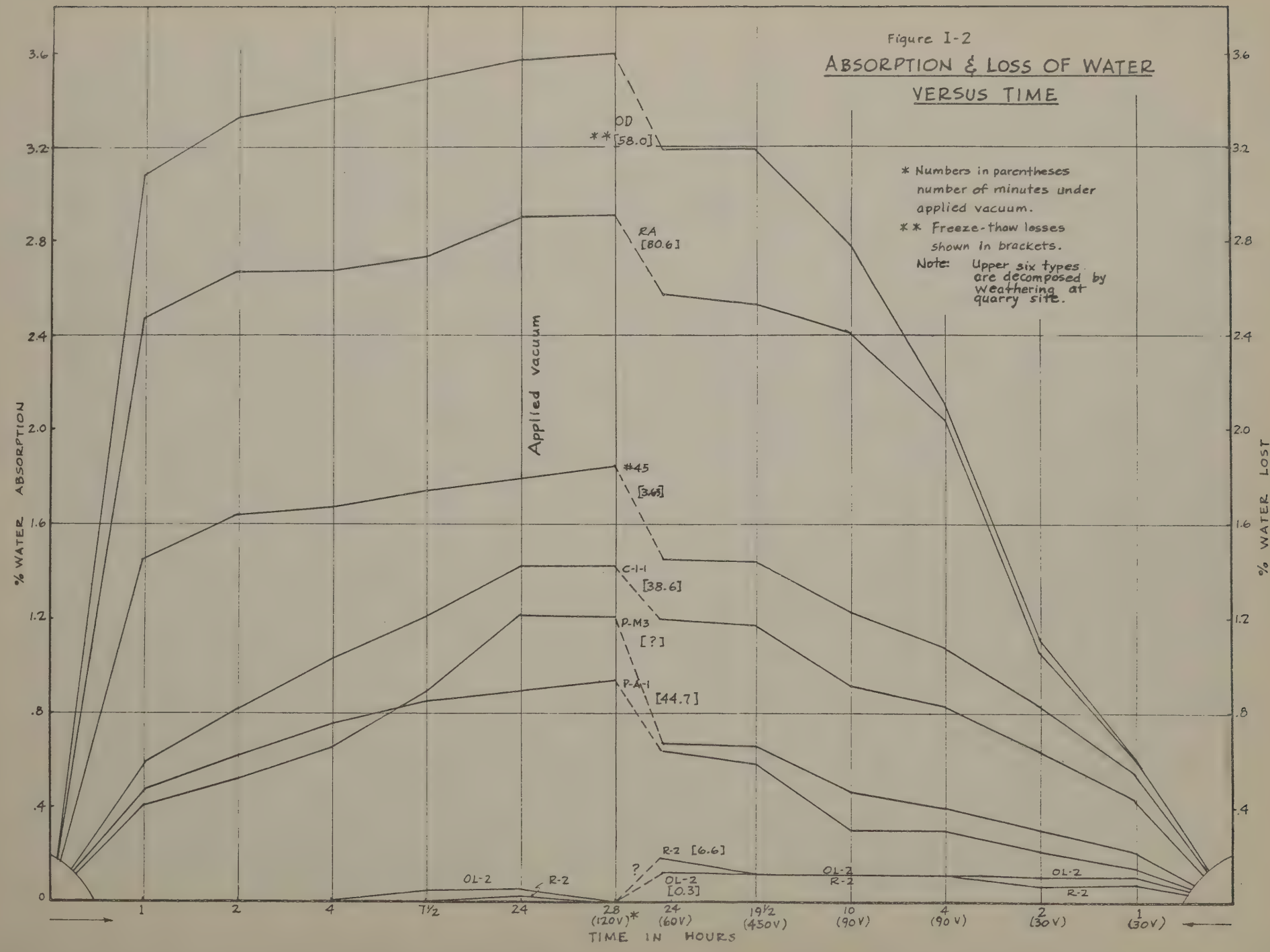
Figure I-1




FROM MILLER & SENECHAL, 1962

Figure I-2

# ABSORPTION & LOSS OF WATER VERSUS TIME



The saturation curves are placed in a mirror position to the vacuum-dry curve on Figure I-2 and I-3.

Two contrasting types of curves are apparent, a curve with a flattened top and a curve with a pointed peak. The flattened tops in rocks with high water absorptions are aggregates with high soundness test losses and some have poor service records; the peaked curves are from rocks with good service records and low soundness losses. Rocks with very low absorptions do not have a consistent pattern, but such rocks are almost never "problem aggregates". Rocks 8a, 3b, and 1b are far from saturated at 18-½ hours of soaking at atmospheric pressure so that evacuation for 3 hours causes a significant and abrupt entry of water into unfilled rock interstices. The same water is removed without difficulty in 460 minutes of actively applied vacuum (21.5 hours in vacuum oven) as indicated on the Figure I-3. Conversely, the rocks which are basically unsatisfactory retain water even in 870 minutes of actively applied vacuum (28 hours in vacuum oven).

The rocks of questionable quality such as O-D, R-A, C-1-1, P-A-1 and P-M-3 are all wet-dry sensitive and some expand on saturation (see section on Wetting and Drying) indicating the likelihood of expansive, interstitial clays. A logical interpretation is that the pores are filled with clays and the water is pulled into the rock by rapid diffusion through water-hungry clays which fill the small pores. Hence on evacuation with the samples immersed in water little additional water enters. Water is lost at a relatively steady rate because of the diffusion processes, when specimens are "vacuum dried". Hence no sharp peaks are present at the inter-sections of the two curves.

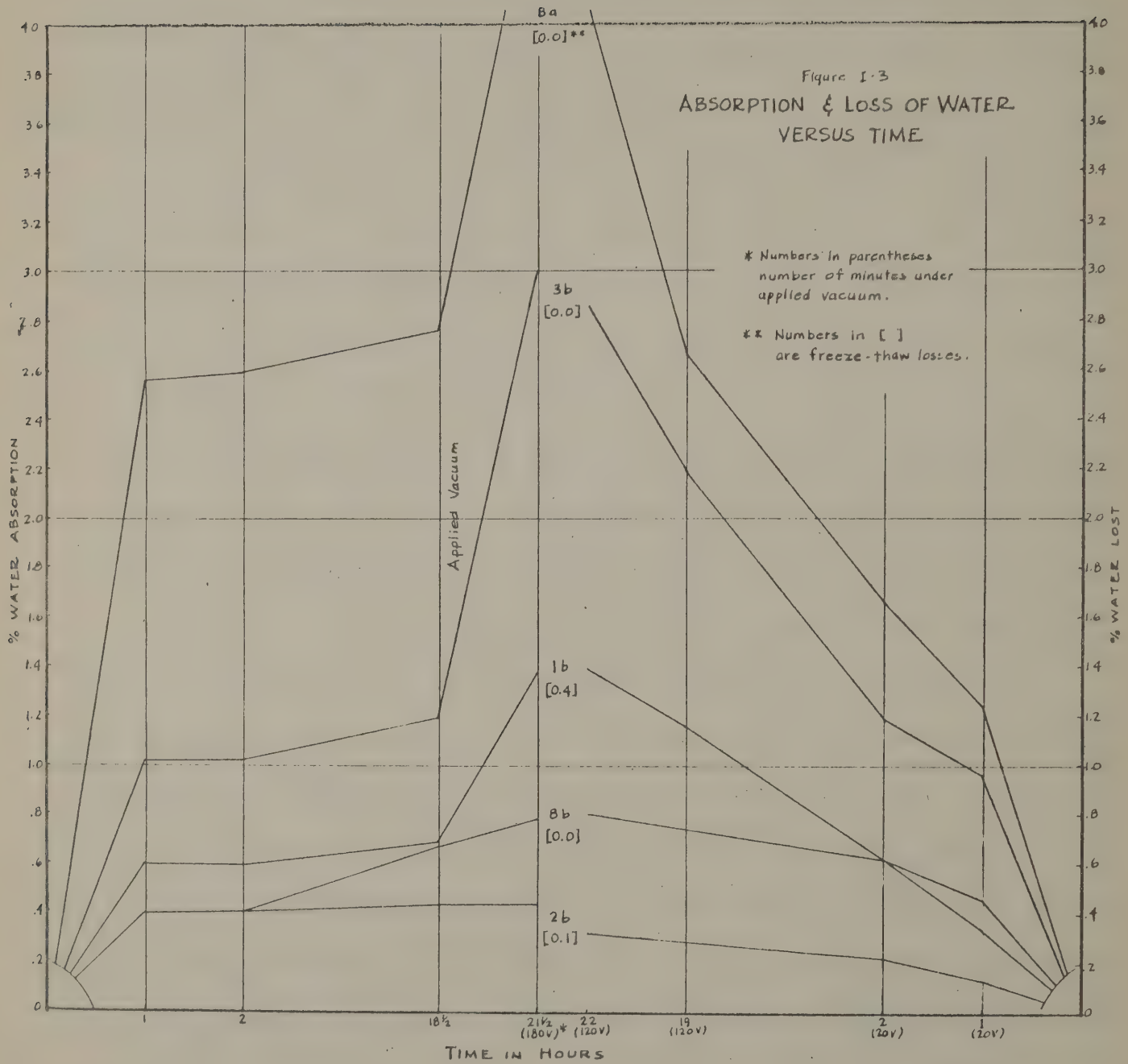


Figure I-3
ABSORPTION & LOSS OF WATER VERSUS TIME
* Numbers in parentheses number of minutes under applied vacuum.
** Numbers in [ ] are freeze-thaw losses.
8a [0.0]**
3b [0.0]
1b [0.4]
8b [0.0]
2b [0.1]
Applied Vacuum
% WATER ABSORPTION
% WATER LOST
TIME IN HOURS
1
2
18½
21½ (180V)*
22 (120V)
19 (120V)
2 (20V)
1 (20V)

An attempt has been made to "standardize" the vacuum dry-saturation curves. Figure 1-4 and 1-5 are a series of curves which were run under these more standard conditions on 25 more specimens of varying absorptions and freeze-thaw losses. The results are, not wholly consistent in character with the curves of Figure 1-2 and 1-3. However the strong tendency for freeze-thaw sensitive rocks to absorb water rapidly and to retain water on evacuation is verified.

The following conclusions seem in order:

1. The major ratio which indicates high freeze-thaw sensitivity is the ratio of the quantity of water gained on "vacuum saturation" to the water lost in 14 hours of vacuum. In every case of high freeze-thaw loss and high water absorption (over 0.6%) this difference (expressed as a steep slope angle) between the two is great.
2. More work needs to be done to standardize the conditions, such as time of vacuum, amount of vacuum, nature of water trap in vacuum system, temperature, size of specimens, relationship of water content and clay content to water loss, and initial drying conditions. Two sound rocks, 7a and 6b, were similar in water gain and water loss characteristics to the freeze-thaw sensitive rocks. No explantion can be given at this time, but standardization of conditions may eliminate some inconsistencies.

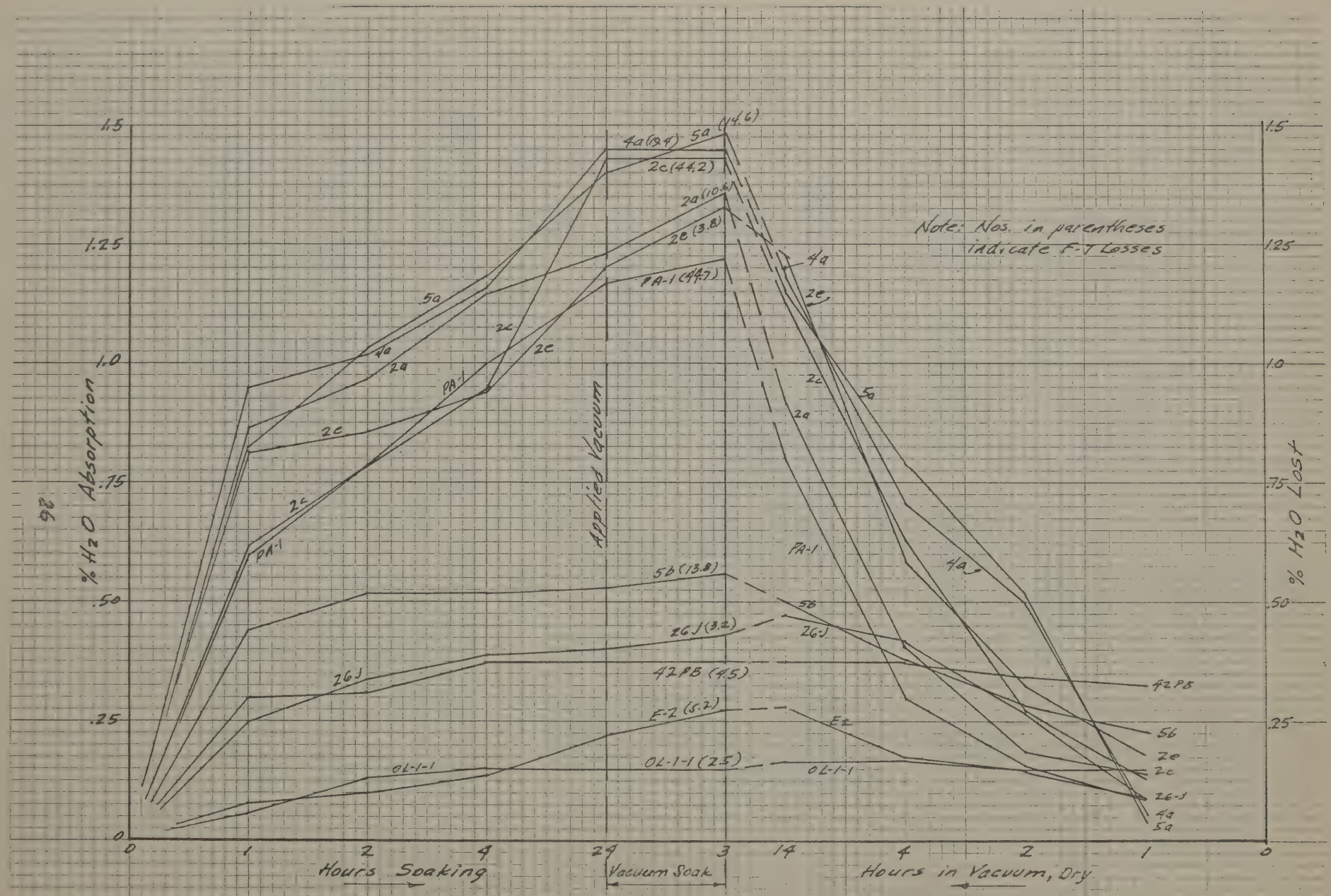



Figure I-4

HIGH FREEZE-THAW LOSS SAMPLES
ABSORPTION AND LOSS OF WATER

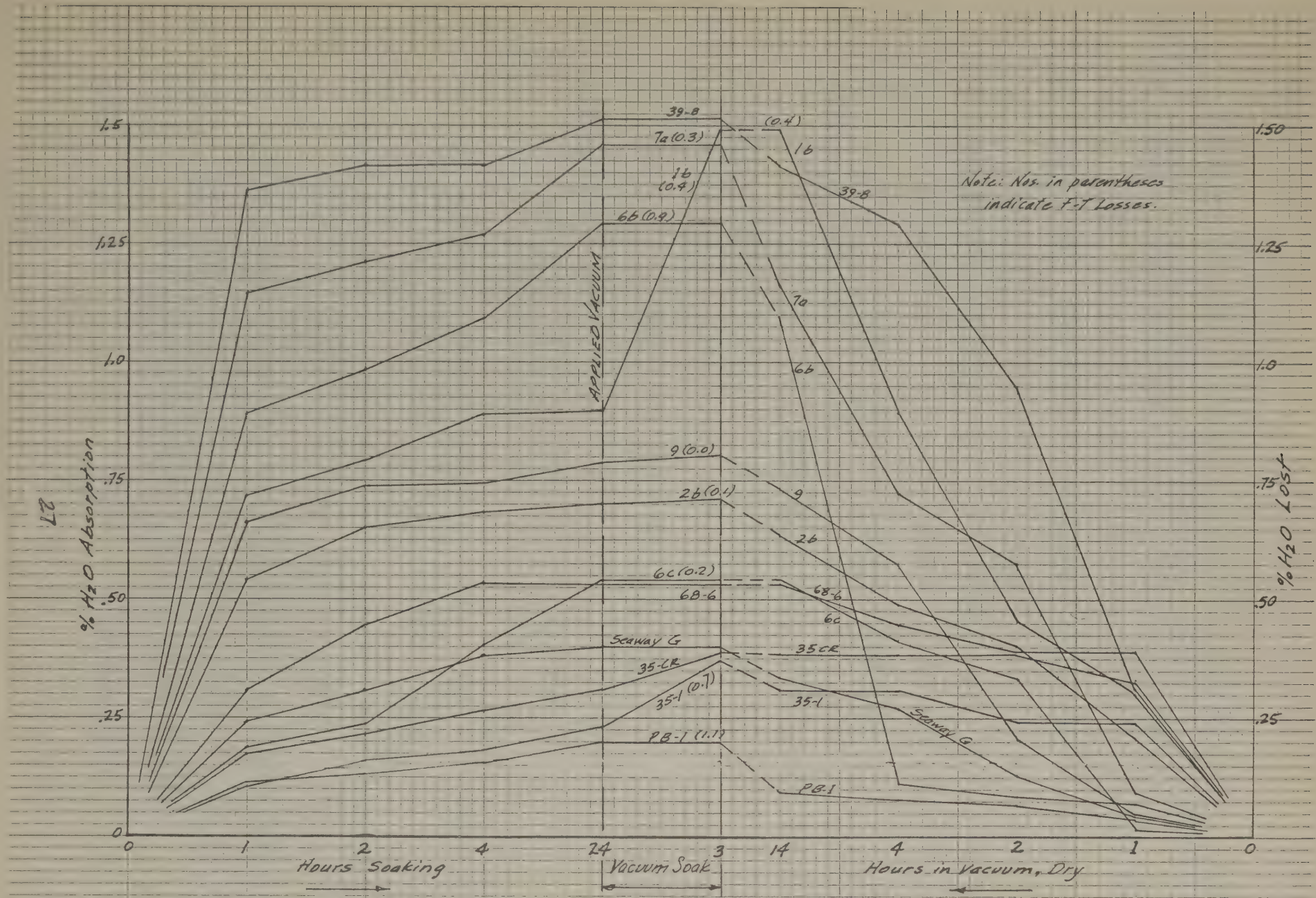



Figure I-5

LOW FREEZE-THAW LOSS SAMPLES

ABSORPTION AND LOSS OF WATER

3. Number 45 chert from the Onondaga formation (Dunn and Ozol, 1962) had a very low freeze-thaw loss (3.65%) and high sodium and magnesium sulfate soundness losses. Judging from the latter losses the freeze-thaw loss seemed significant. Chert of this type also caused popouts in a highway of non-air entrained concrete. The vacuum-absorption-vacuum-loss accurately demonstrated the true freeze-thaw sensitivity of this rock. (for more data on #45 chert see Dunn and Ozol, 1962).

Longitudinal Compressional Wave Velocities

Sonic velocities were determined on ½ inch cores about 1 to 2 inches long which were cut from all blocks studied. Cores were taken perpendicular and parallel to the bedding and if the full orientation of the block were known, two cores were cut parallel to the bedding, one north-south, one east-west. For details of the procedure, see appendix B-10, pg.203.

Measurement of sonic velocities is believed to be a very important method of evaluating subtle differences in aggregate soundness. Raw measurements of the type done in the present study are valuable in that they disclose minor imperfections which influence the soundness of aggregate. Most rocks which are believed to be unsound have low sonic velocities. However, many of the rocks with low sonic velocities have no apparent unsound characteristics as indicated by the other tests.

According to the literature the sonic measurements which have been determined are similar in scale to those previously determined.

For example:

| | | |
|---|---|---|
| Manlius limestone | | 18,300 ft./sec. |
| Solenhofen limestone (Ahrens and Katz, 1963) | | 17,800 ft./sec. |
| Solenhofen limestone | | 19,500 ft./sec. (atmos. p) |
| Marble, Rutland, Vt. | | 19,200 ft./sec. (10 bars) |
| Argillaceous limestone, | ⊥ bedding | 18,700 ft./sec. (10 bars) |
| | ∥ bedding | 19,700 ft./sec. (10 bars) |

(Hughes and Cross, 1951)

| | |
|---|---|
| Lithographic limestone | 18,000 ft./sec. (10 bars) |
| Dolomite | 18,300 ft./sec. (10 bars) |

(Birch, 1960)

The following general relationships can be made between sonic velocities and other characteristics:

1. Of the 79 cases where sonic velocities were measured perpendicular to the bedding, 63% of the time the slow velocity was perpendicular to the bedding. The exceptions to the trend were massive apparently homogeneous limestones and dolomites which were in the category of "thick bedded." Thus bedding discontinuities seem to cause sonic discontinuities and reduce the average sonic velocities.

2. Sonic velocities tend to decrease with increase in the percent of insoluble residues.
3. Sonic velocities tend to decrease with dolomite content and with percent water absorption.

A complete interpretation of the interrelationship of sonic velocity data with other information would require an extensive study which is not possible in the present program.

Shear Wave Velocities and Poisson's Ratio

Largely because of the availability of equipment, prepared samples and personnel, determinations were made of shear wave velocities ($V_T$) and by relating them to the longitudinal compressional wave velocities ($V_L$), Poisson's ratio ($\sigma$) could be calculated according to the following expression

$$\sigma = \frac{1}{2}\left[1 - \frac{1}{\left(\frac{V_L}{V_T}\right)^2 - 1}\right]$$

The results are tabulated on Table A-8. Shear wave velocities were measured on the same sample as compressional velocities.

Poisson's ratio is defined as the ratio of transverse contraction per unit dimension of a bar of uniform cross-section to its elongation per unit length when subjected to a tensile stress. The magnitude of Poisson's ratio is largely a function of the elasticity of the sample.

Rocks with high Poisson's ratio (over 0.30) are sound rocks in tests. However, rocks which have low Poisson's ratios may be either sound or unsound and are generally highly water absorptive.

A complete analysis of this aspect of the research is not possible at present.

Thermal Expansion

The thermal expansion of 24 test blocks was determined in the range -90° to +160°F in three directions, perpendicular to bedding and two directions parallel to the bedding at right angles to each other. The technique for making the determinations is described in the appendix, B-9, pg. 203 .

The coefficient of thermal expansion is related most obviously to two characteristics: (1) the calcite dolomite ratio and (2) the total insoluble residue. Figure I-6 relates the thermal expansion to the percent dolomite. It is quite clear that the thermal expansion increases with dolomite content, ranging from about $3.5 \times 10^{-6}$ in/in/F° for pure limestone to $9.5 \times 10^{-6}$ for pure dolomite. Impurities have a tendency to reduce the thermal expansion so that for a given dolomite content the impurities tend to drop the thermal expansion so that it falls below the median line on Figure 1-6.

The influence of thermal expansion characteristics of aggregate on concrete is not clear. According to Pearson (1941) working at temperatures below freezing points for water, a low coefficient of thermal expansion for aggregate indicates possible reduction of durability of concrete. However Walker, Bloem, and Mullen (1936), experimenting in the range of 40°F to 140°F, concluded that a high coefficient of thermal expansion for aggregate and large difference between the thermal expansion of the constituents of concrete indicate unsoundness.

Within the freezing-thawing range, Collon (1954) says that where the difference in the thermal expansion coefficient for material in

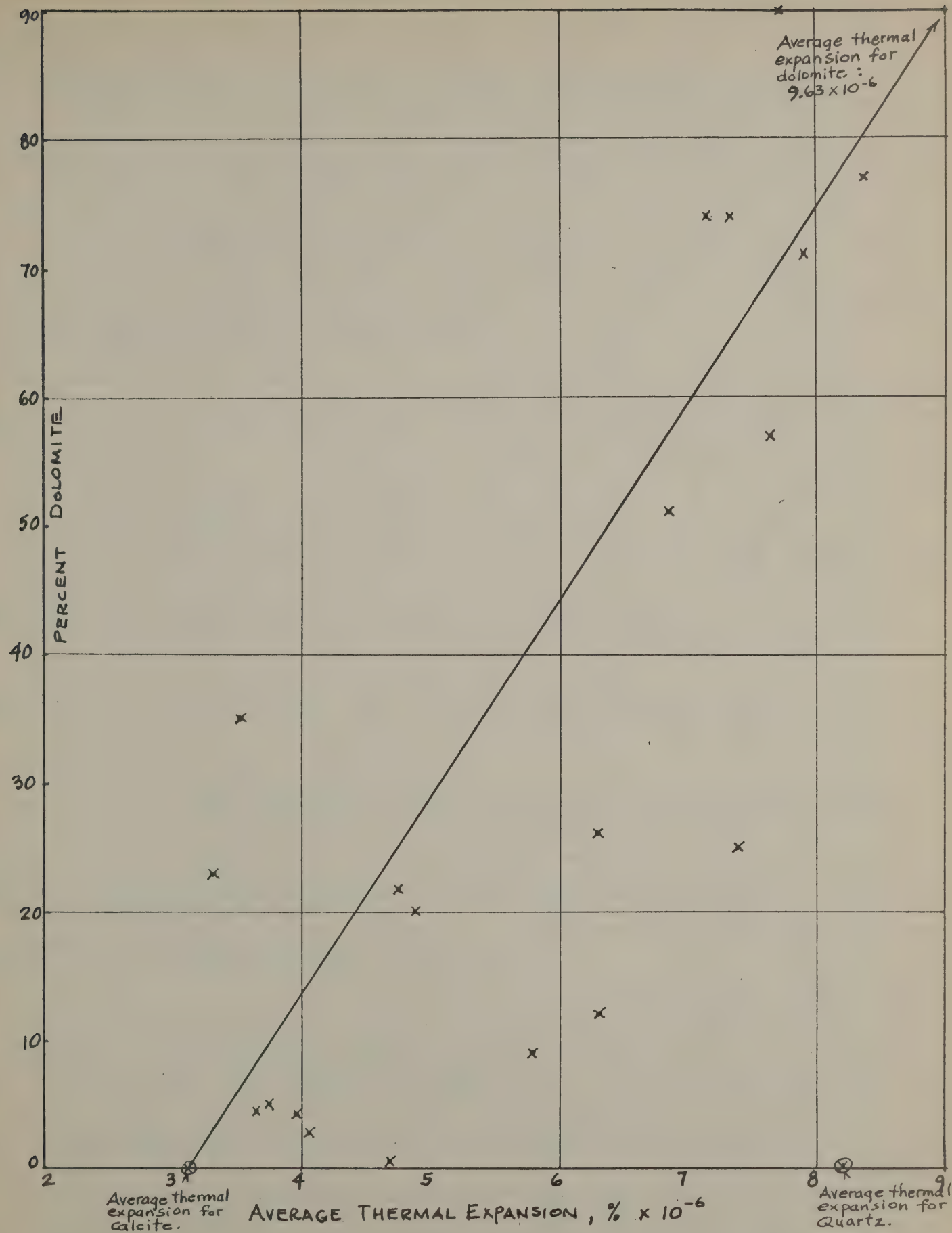



Figure I-6

AVERAGE THERMAL EXPANSION VS. % DOLOMITE

concrete exceeds $3 \times 10^{-6}$, caution should be exercised.

Typical coefficients of thermal expansion for some common materials in in/in/°F are:

| | |
|---|---|
| Limestone | $1.2$ to $6.5 \times 10^{-6}$ |
| | $6.0$ to $12.0 \times 10^{-6}$ (moisture dependent) |
| Concrete | $3.2$ to $7.8 \times 10^{-6}$ (dependent mostly on the coarse aggregate used) |
| Calcite along c-axis | $23.58 \times 10^{-6}$ |
| Calcite perpendicular c-axis | $-5.22 \times 10^{-6}$ |
| Quartz | $5.6$ to $8.0 \times 10^{-6}$ (depending on orientation) |

It would seem from the above tabulation that coarse grained calcitic (and possibly dolomitic) rocks or carbonate rocks with strong degrees of preferred orientation of the c-axis of the crystals might cause potentially unsound concrete. None of the rocks studied in the present program seemed to be in the deleteriously expansive category.

Sulfate Soundness, Freeze-thaw and Deval Abrasion Tests

All carbonate rocks which were studied in this project were subjected to standard magnesium sulfate, sodium sulfate*, freeze-thaw and modified Deval abrasion tests in the N.Y.S.D.P.W. laboratories according to State specifications.

The results are on Table A-6, pg.172. It should be noted here that the tests as given are probably more severe than the normal tests run on material taken from aggregate piles at plants. The

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* According to 1958 State specifications. As of January 2, 1962 the sodium sulfate soundness test is no longer required by N.Y.S. D.P.W.

abrasion of corners and the splitting of weak pieces as the particles are processed tends to reduce the number of weak points which can be attacked by the testing media. However, the tests are internally consistent and produce valuable relative results.

Of 80 carbonate rocks which were tested, 7% failed the sodium sulfate soundness test, 12% failed the magnesium sulfate soundness test and 51% failed the freeze-thaw test. All which failed the sulfate soundness test failed the freeze-thaw test also. The average sodium sulfate tests loss was 1.5%, magnesium sulfate 4.6%, and freeze-thaw 11.7%.

Additional studies were conducted at Rensselaer on ½" cores, fragments and sawed cubes of carbonate rocks, but the procedure was abandoned when it was found that surface films of oil or grease from handling were probably adversely influencing the results. None of the results of this phase of the research are included, because they were inconclusive and incomplete.

Nine samples of typical Catskill graywackes from operating quarries were subjected to water absorption, duplicate magnesium sulfate soundness and freeze-thaw tests according to N.Y.S.D.P.W. specifications except for size, see Table A-6.

Eight of 18 tests were unsatisfactory for the magnesium sulfate test and 15 of 18 did not pass the freeze-thaw test.

Failures in the freeze-thaw test were not limited to any particular formation or rock type. Many of the failures were less than 20% and it seems dubious that such losses are significant considering the apparent severity of the test and the fact that the aggregate

particles did not go through the normal abrasion in a crushed stone plant. Only 11 out of 40 samples tested are believed to be obviously inferior under the conditions of the test. Six of these were also over the loss limits for class B aggregate in the magnesium sulfate soundness test.

As a group the rocks studied had excellent results in the abrasion test with only 7 failures noted.

Reproducibility of the Magnesium Sulfate Soundness Test

The reproducibility of the magnesium sulfate soundness test was studied for Catskill graywacke as part of a special project (Miller and Senechal, 1962). Tests, with standard solutions, standard temperatures and time were performed on cubes of comparable size cut from one-inch slabs. Two blocks of homogeneous-appearing sandstone with relatively consistent water absorption values (to within 30%) were used with the results as shown in Figure I-7.

The loss from specimen 40-1R was from 0.39% to 0.77% for 12 blocks, average 0.57%, standard deviation 0.10%, (see Figure I-7). Specimen 9-13-14R had a range of losses from 1.1% to 8.9%.

The ability to duplicate the magnesium sulfate soundness test on the Catskill graywacke specimens of various shape but comparable size was checked at Rensselaer by Miller and Senechal (1962, Table 1). The average magnesium sulfate soundness loss for 15 sawed cubes (average of 50 to 60 grams) was 7.8%; for 12 cores (average 17 to 20 grams) 11.9%; for 40 chips (average 30-40 grams) 32.1%. Even considering the variable size and surface area of the test specimens, the much higher loss for fragments seems to be significant.

FIGURE 1-7

REPRODUCIBILITY OF $MgSO_4$ SOUNDNESS TEST

40-1R

| | | | |
|---|---|---|---|
| | .55 | .71 | .53 |
| .51 | .57 | .63 | |
| .50 | .53 | | .39 |
| .45 | .77 | .67 | |

9-14-13R

| | | | |
|---|---|---|---|
| | 8.0 | | 7.3 |
| 1.1 | | 2.3 | |
| | 1.9 | | 8.9 |
| 1.2 | | 1.8 | |

From Miller and Senechal, 1962

Based on the Rensselaer research on carbonate rocks and graywackes it has been concluded that tests on small specimens, particularly cut specimens, are not meaningful. This is partly because of the lack of averaging (which occurs with larger specimens) and partly due to the fact that frequent handling and sawing of specimens may spot them with oil and radically alter the test results. None of these test data are included in the present report because of the lack of significance, but some data are recorded by Miller and Senechal (1962) for permanent record.

Generally the results from cores and cubes seem comparable. However, chips show an average loss which is several times that of cubes or cores of comparable size. The presence of irregular surfaces and sharp corners on the fragments probably accounts for higher losses. Presumably aggregate particles which have been subjected to normal processing in a crushed stone plant would have losses more in line with those for cubes or cores.

Viscosity of Testing Solutions

A critical variable in sulfate soundness and freeze-thaw tests is the viscosity of the various solutions, because viscosity has an influence on the rate of penetration of water into aggregate particles.

The viscosity of a standard magnesium sulfate solution (sp. g. 1.300, T-15°- 25°C) was found to be 8.50 times that of water as measured with an Ostwald-Frensk Viscosimeter. Two simple experiments were performed to obtain some empirical evaluation of the significance of this viscosity difference.

In the first case, a piece of sawed, oven dried sandstone with a plastic coating on one surface as a "window" was immersed in water. Water was seen to permeate the specimen in a matter of minutes. Under the same conditions the standard magnesium sulfate solution did not penetrate visibly in several hours.

As a further check, 20 pieces of carbonate rocks of various water absorptions were placed in a standard magnesium sulphate solution for 18 hours, removed and split in two. The halves were then sprayed with a $BaCl_2$ solution to produce a white $BaSO_4$ precipitate wherever the sulfate penetrated. The maximum distance of penetration was 0.1 inch.

Inside of the sulfate-rich rim zone the carbonate rock specimens seemed to be damp, suggesting that the solution split into a salt-poor fraction moving by capillary forces deeply into the specimens

and a salt enriched rim moving slowly by diffusion. A possible corroboration of this phemomenon may be in the accumulation of crystals which blocked the mouth of the capillary tube of the viscosimeter when attempts were made to measure the viscosity of the standard sodium sulfate solution. The small amounts of liquid rising into the tube may have been salt-poor, causing super-saturation at the mouth of the tube.

The subject of splitting of salt solutions merits further and more systematic study, because it implies that crystals first grow in and on aggregate particle rims during the saturation period. For a more complete discussion of some phases of this phenomenon see Mohammed (1963, pp. 27-31).

From several lines of evidence it seems reasonable to conclude that the magnesium sulfate soundness test, and possibly the sodium sulfate soundness test, are primarily surficial tests (unless, perhaps, large, deep pits or cracks exist) which are used to predict volume effects of freezing and thawing. The lack of reproducibility could be caused by many different things as well demonstrated in the literature, but a major consideration in this research is believed to be minor amounts of oil on the surface of particles.

## Sulfate Tests and Pore Size Distribution *

An effort was made to determine the effect of pore-size distribution

*Portion on graywackes largely paraphrased from Miller and Senechal (1962).

of sandstones on the results of the magnesium sulfate soundness test using a Ruska Permeameter. The details of the techniques used for determining the porosity, pore size distribution and permeability are given by Mohammed (1963) and by Miller and Senechal (1962). The basic procedure is to measure the amount of mercury forced into a core specimen at various pressures up to 2000 pounds per square inch. The porosity at 2000 psi is then the ratio of the volume of mercury forced into the pore space to the total volume of rock.

Figure 1-8 shows a plot of volume of mercury versus pressure for runs of Catskill graywacke sampled from the same block (9-14-21). The difference between the straight lines (calibration curves) and the curved lines (specimen curves) gives the volume of pore space into which the mercury could be forced at each pressure increment.

A slope which is steeper than the calibration curves indicates that mercury is going into the sample and the pressure at which this occurs can be used to estimate the pore size (pore entry diameter is $10^{-4}$ mm $= \frac{2\sigma \cos \theta}{Pc}$ *). Thus the pore size distribution can be determined, e.g., for sample 9-14- 21 the pore size of the greatest abundance lies in the range 0.1640 to 0.0735 X $10^{-4}$mm.

The permeability is related to the area between the curves and the straight lines.

*Where Pc is applied or capillary pressure, and $\sigma$ is the surface tension of mercury, i.e., 480 dynes/cm at 20°C, and $\theta$ is the contact angle of mercury against a solid, 140°.

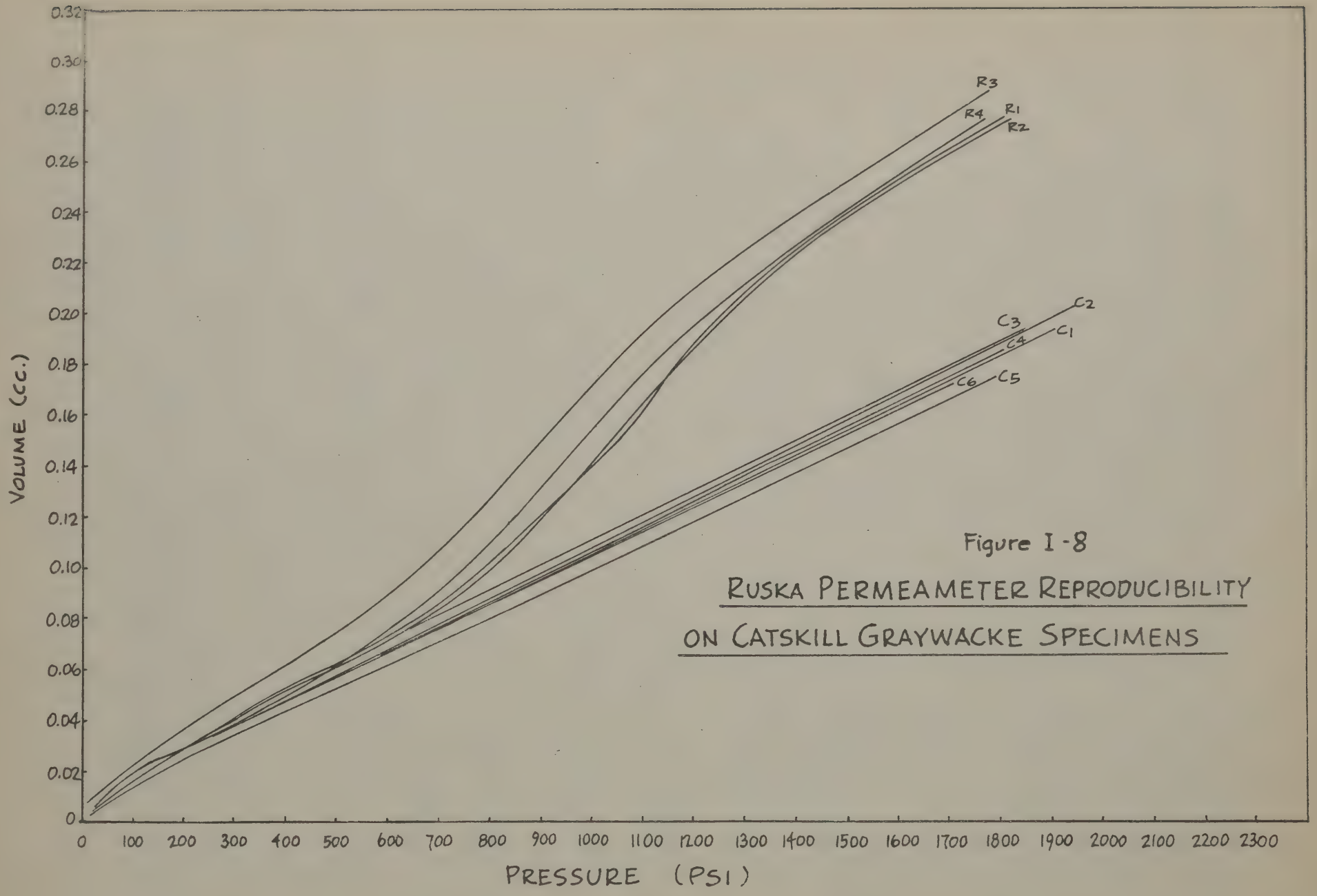



Figure I-8

RUSKA PERMEAMETER REPRODUCIBILITY ON CATSKILL GRAYWACKE SPECIMENS

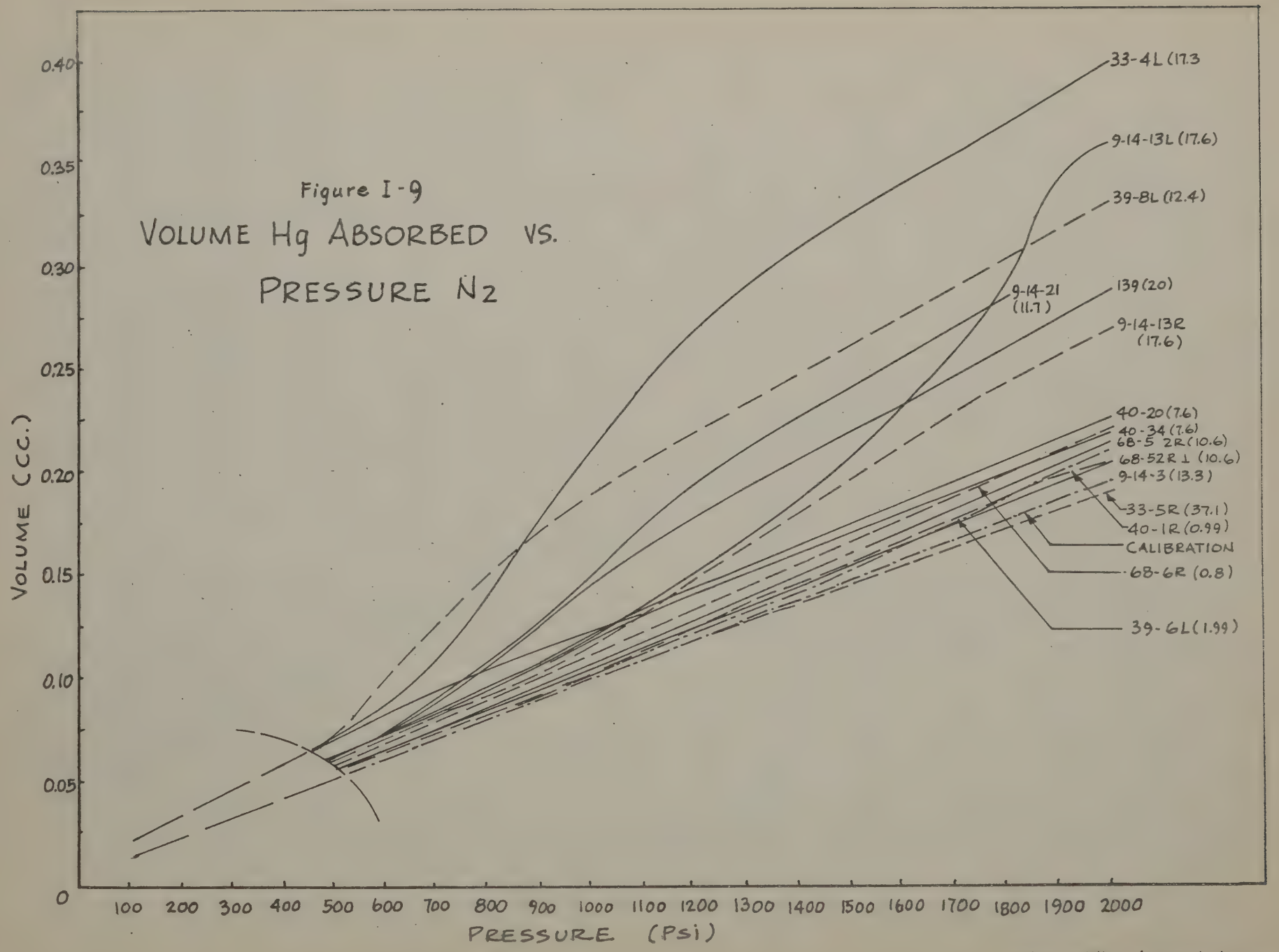
From Miller & Senechal, 1962

Figure 1-8 indicates the reproducibility of the permeameter tests. Each line represents a separate analysis, i.e., the average mercury compression curve has been determined by four analyses on the same rock. The sample has given essentially the same results four consecutive times. Curve $R_3$ is displaced to the left, indicating a higher volume Hg entering the sample. A fine crack was noted and could account for the increased volume.

Fourteen graywacke samples have been analyzed using a Ruska Permeameter. Figure 1-9 shows the results using the same type of plot discussed in the preceeding paragarph. The values for percent loss during the $MgSO_4$ soundness test are given in parentheses on each curve.

Correlation between the porosity, pore size distribution or permeability, as measured with the Ruska Permeameter, and soundness loss is not seen. In fact, samples 9-14-3 and 33-5R indicate that the pore size, porosity, and permeability within the experimental limits are not critical with respect to the specimens' response to the sulfate test.

Similar pore size research on limestones was not possible, because the grain size was too small to allow measurable permeation by mercury at presently available pressures (2000 psi). Pore size work with dolomites produced some measurable results, but the pores were so heterogeneous as to size and distribution that the results were not considered to be significant and are not included.




From Miller & Senechal, 1962

Pore size distribution analysis probably could be made for limestpnes with the higher pressures available in more modern equipment.

## Discussion of Catskill Graywacke Soundness Failures

Although the correlation between various specific characteristics and soundness test failures is poor, it is the opinion of the author that the test failures are primarily due to permeability-porosity characteristics. Some sort of correlation seemed to exist between a high water absorption and a high soundness test loss and between a high mercury absorption and a high soundness test loss on many samples. The lack of correlation of some samples could be caused by oil in the samples (excessive handling) or inability to detect the smaller pores because of insufficient pressures to impregnate them with mercury.

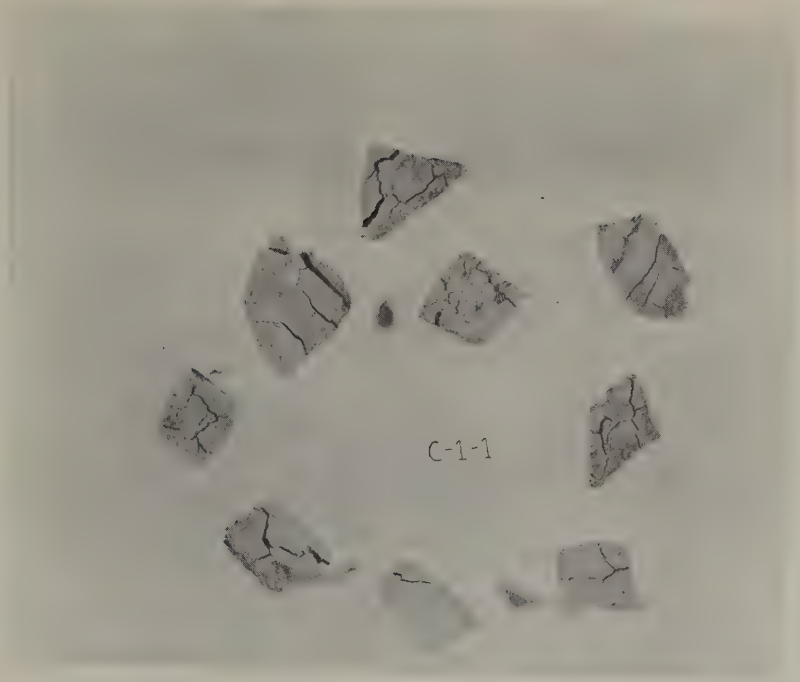
No failures of portland cement concrete due to graywacke are known to the author or to the N.Y.S.D.P.W. Failures due to shale associated with the graywacke have been reported to Mr. Paul Bird of the N.Y.S.D.P.W. (oral communication).

## Wetting and Drying

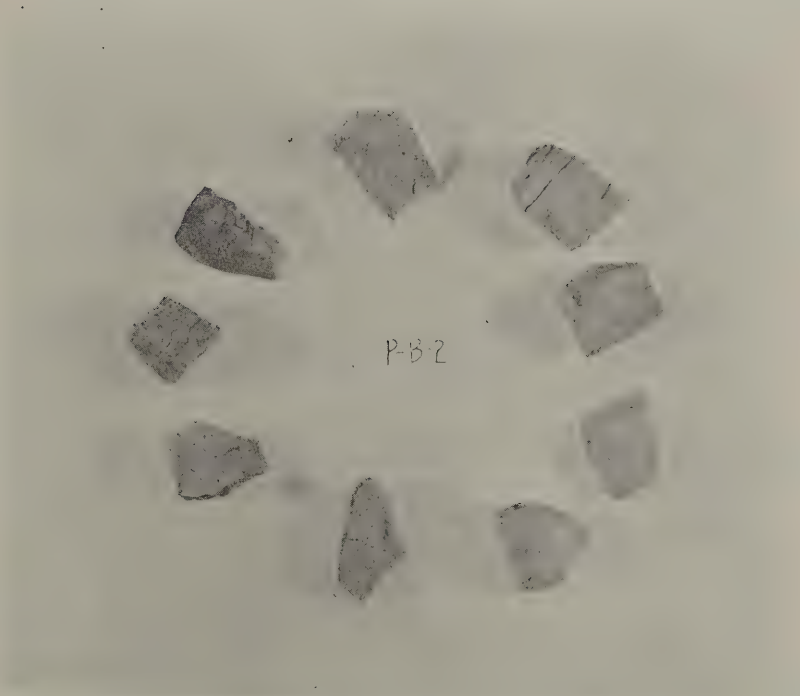
Ten carbonate rocks which did not contain shale except along minor partings or stylolites* were subjected to wetting and drying by Mahdi Mohammed, a graduate student at Rensselaer. Although the work was not done systematically, the results are worthwhile including in the present report, because they indicate an area of needed research on New York rocks.

*Stylolites are zig-zag lines of weakness (and permeability) which are almost ubiquitous in limestone and dolomites. They are solution and/or pressure phenomena of uncertain origin.

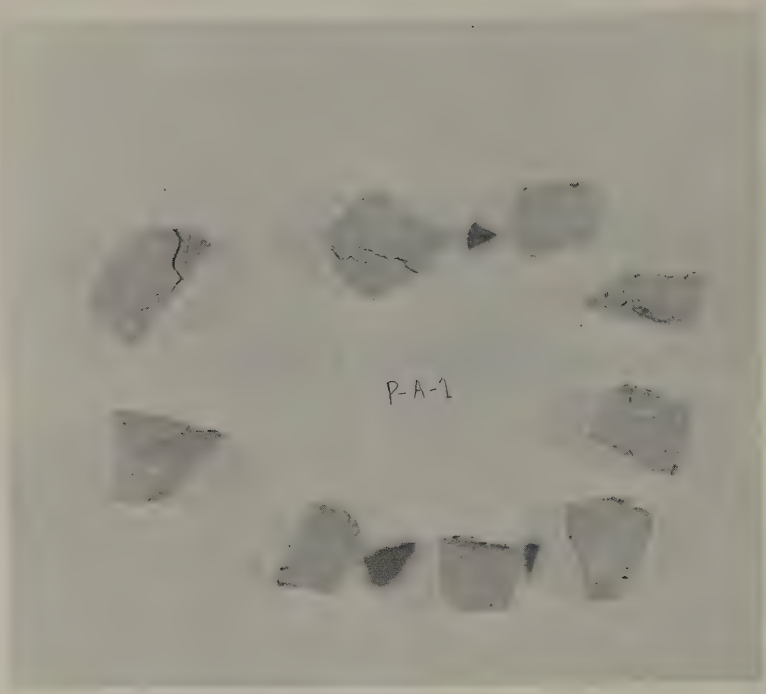
Ten samples of each carbonate rock, approximately one inch square, were alternately soaked in tap water at room temperature for 24 hours or more and dried at 105° for 24 to 72 hours. At three months (approximately 25 cycles) sample C-1-1 from the Lockport formation began to crack conchoidally. In six months (about 50 cycles) two samples of Pamelia formation, P-B-2 and P-A-1, also developed noticeable fractures, some of which are conchoidal. After approximately 100 cycles of wetting and drying, samples OL-1-1 (Clark Reservation member of the Manlius formation) and E-b-1 (Jamesville member of the Manlius formation) developed minor cracks along stylolites and bedding planes. Photographs I-1, I-2 and I-3 show the condition of the three most deteriorated samples. The cracks in Ol-1-1 and E-b-1 are not considered to be significant because most limestones should fail similarly on wetting and drying and yet have no necessary ill effects when confined in concrete.




PHOTOGRAPH I-1 WET-DRY DETERIORATION OF C-1-1




PHOTOGRAPH I-2 WET-DRY DETERIORATION OF P-B-2




PHOTOGRAPH I-3. WET-DRY DETERIORATION OF P-A-1

Relationships Between Various Parameters

Attempts have been made to find correlations between the following measured characteristics by plotting them graphically against each other:

1. Percent dolomite and thermal expansion for carbonate rocks, Figure I-6, pg. 33 . The averaged coefficient of thermal expansion for calcite is about $3.09 \times 10^{-6}$ in/in/$^{o}$F, for dolomite about $9.63 \times 10^{-6}$ in/in/$^{o}$F, and for quartz about $8.25 \times 10^{-6}$ in/in/$^{o}$F. A straight line between the dolomite and calcite averages of Figure I-6 should represent the position of rocks which are pure calcite-dolomite mixtures. The dots are plots of percent dolomite versus expansion. Several rocks are close to the line. Almost all rocks which deviate strongly to the right of the calcite-dolomite line are quartz-rich and if a correction is made for quartz content, the points move relatively close to the calcite-dolomite line.

   An attempt to determine the thermal expansion contribution of the clays as determined normatively was made but no correlation could be seen. Apparently the clays have thermal expansions which range from less than calcite to close to that of dolomite.

2. Freeze-thaw loss and magnesium sulfate soundness loss. Figure I-10 is a plot of the magnesium sulfate soundness test percent loss against the freeze-thaw test percent loss for carbonate rocks (x) and graywackes (⊗). The block in the lower left hand corner is the area in which lie acceptable tests

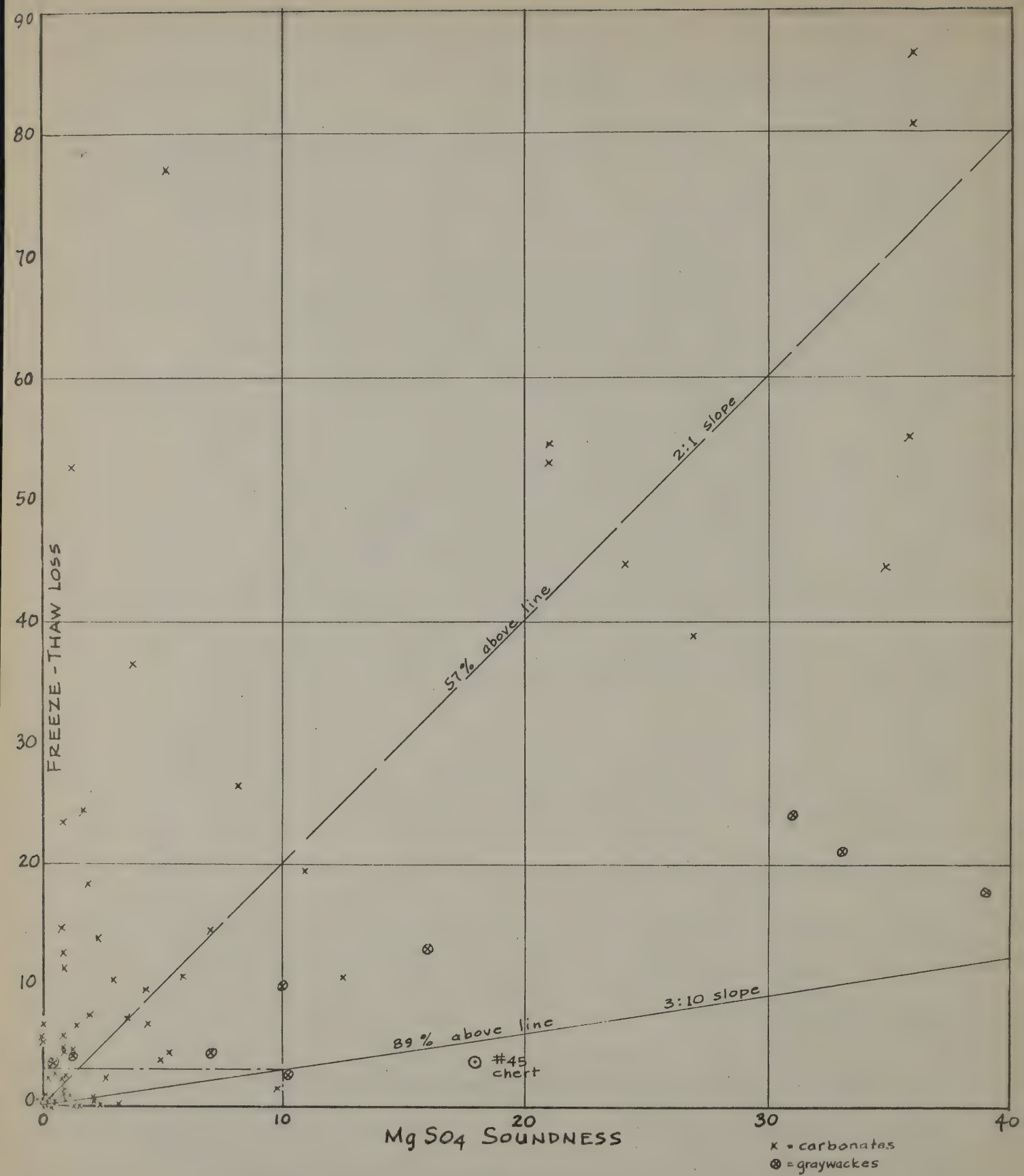



Figure I-10

MgSO4 SOUNDNESS VS. FREEZE-THAW LOSS

(limits of Type B stone). The 3:10 slope line is defined by the loss ratio of the maximum allowable loss for acceptable magnesium sulfate soundness loss (10%) for rock to be used in portland cement concrete.

If the two test limits were of comparable severity, points should be concentrated along the 3:10 slope or be equally distributed about the line. It is obvious from this that the arbitrary test limits are not comparable. A 2:1 slope (20% freeze-thaw loss versus the present 10% magnesium sulfate loss) would place 24 points below the curve and 26 points above the curve. A 10% to 20% limit for the freeze-thaw test would seem more comparable than the present 3%. Figure I-10 in part merely repeats the previous statement (pg.50 ) that the average freeze thaw loss is higher (11.7%) than the average magnesium sulfate soundness test (4.6%) and seems to be inconsistent with the established test limits.

The position of the graywacke points is difficult to explain although their position is probably significant. Possibly a chemical or absorptive reaction with the sulfate solution may occur (as suggested by Miller and Senechal, 1962). The position of a porous chert (#45 of Dunn and Ozol, 1962) is placed on the plot for reference. The apparent inconsistency in position of carbonate, graywacke and chert points has no apparent answer at this time.

It would seem that more research on carefully selected test blocks of different lithologies should be done to check test limits. In the authors opinion test limits should be low when stockpiles are tested but should be high when tests are on individual layers.

3. Water absorption and magnesium sulfate soundness test loss. Figure I-11 is a plot of percent water absorption versus percent magnesium sulfate soundness test loss. The X's are carbonate rocks and the circled X's are graywackes. A rough relationship exists in that all sulfate soundness losses which are over 10% are for rocks which have water absorptions of 0.6% or over. However, 12 rocks with absorptions of over 1% are under the 10% limit including the two most absorptive carbonate rocks and three carbonate rocks with no soundness loss.

Figure I-12 is a plot of magnesium sulfate soundness test loss against absorption for graywackes showing a fairly good correlation. The data seem to indicate that a minimum absorption is necessary before a soundness failure can occur, but high absorption alone is not a requisite for failure.

4. Water absorption and freeze-thaw test loss.
Figure I-13 is a plot of percent water absorption against percent loss on the freeze-thaw test. A rough relationship may exist between high water absorption and freeze-thaw loss, but 9 specimens with over 0.6% absorption had less than ½% freeze-

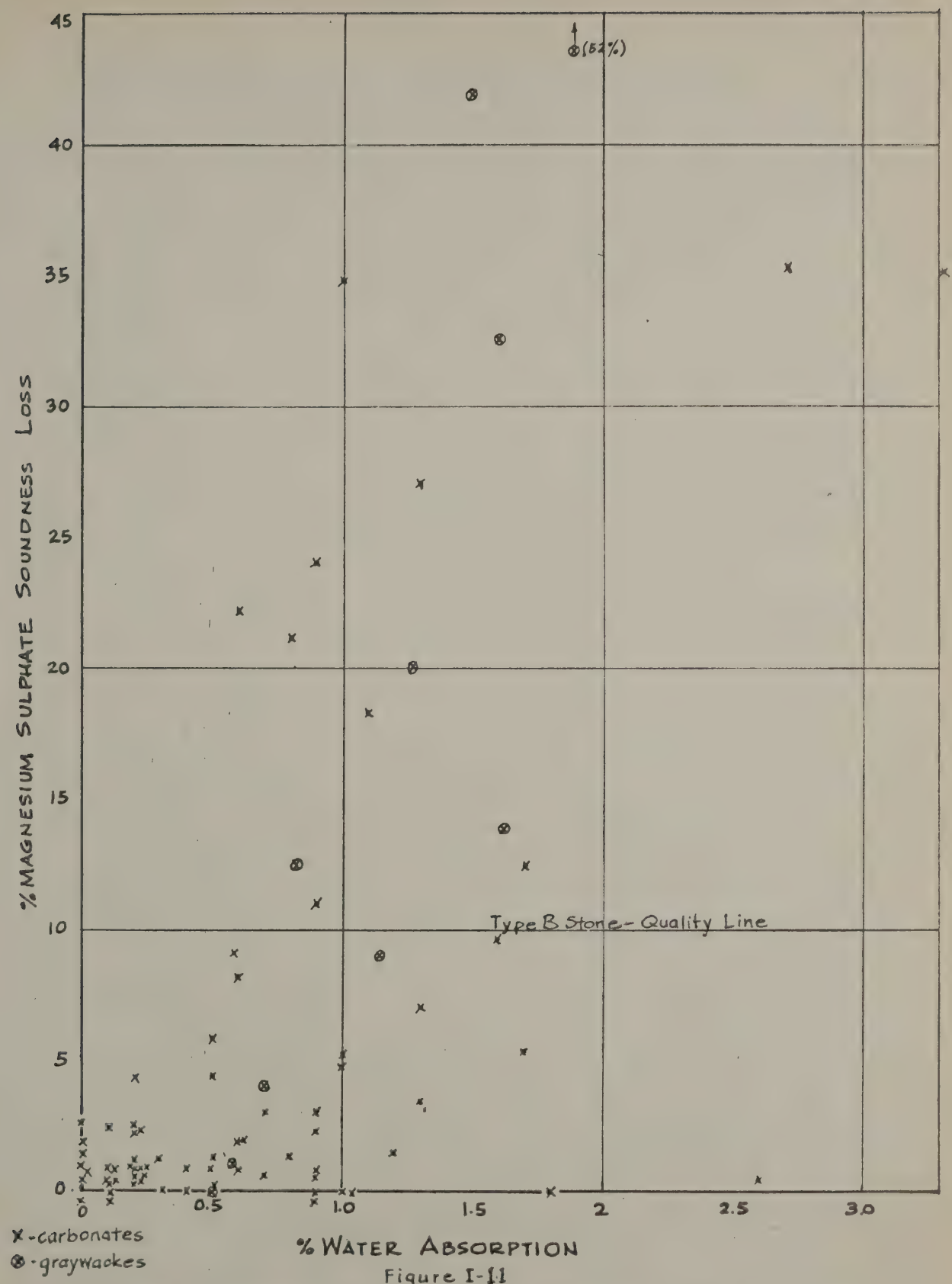
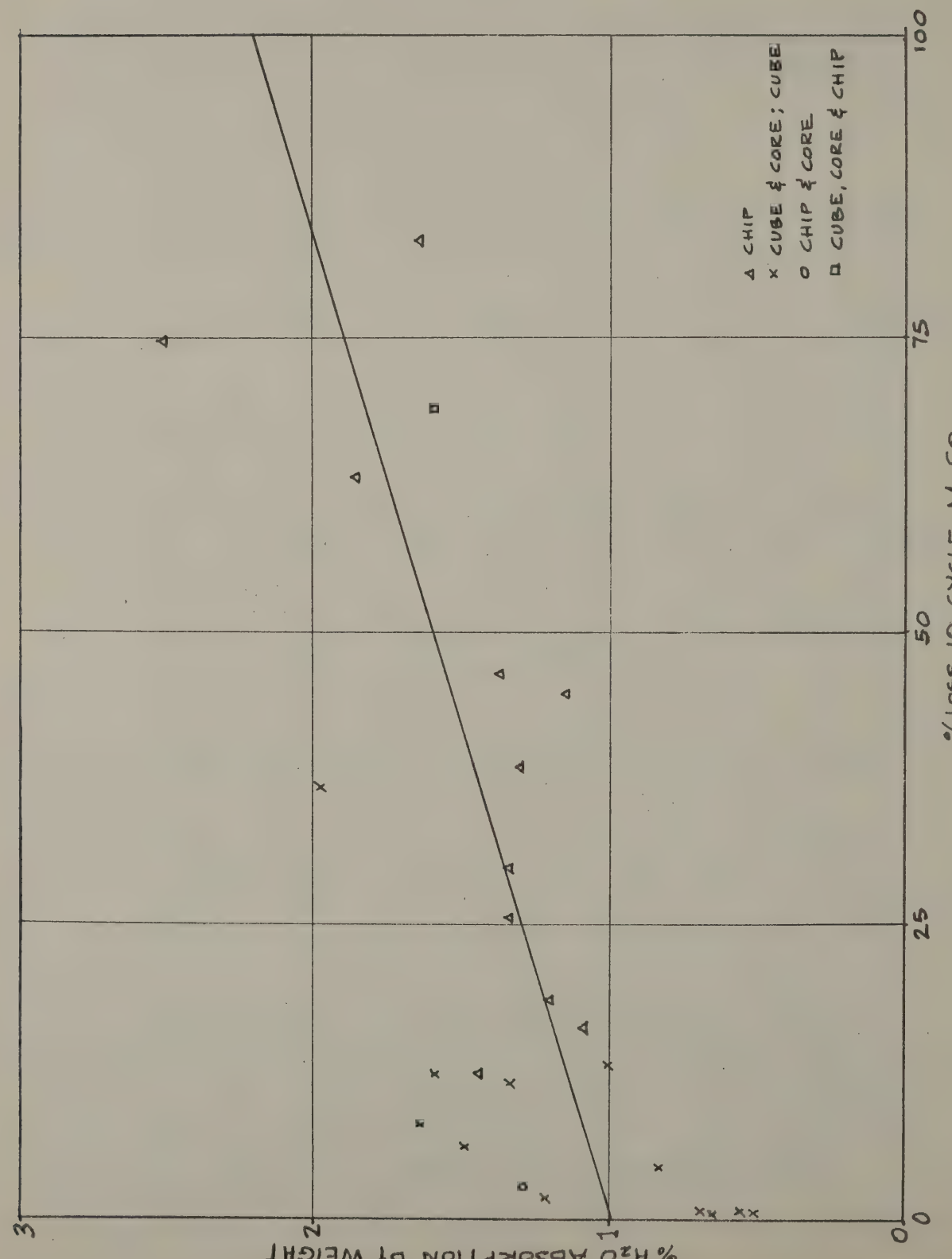



Figure I-11

WATER ABSORPTION VS. MAGNESIUM SULPHATE SOUNDNESS

Figure I - 12

## WATER ABSORPTION VS. 10 CYCLE $MgSO_4$ TEST FOR CATSKILL GRAYWACKES




FROM MILLER & SENECHAL, 1962

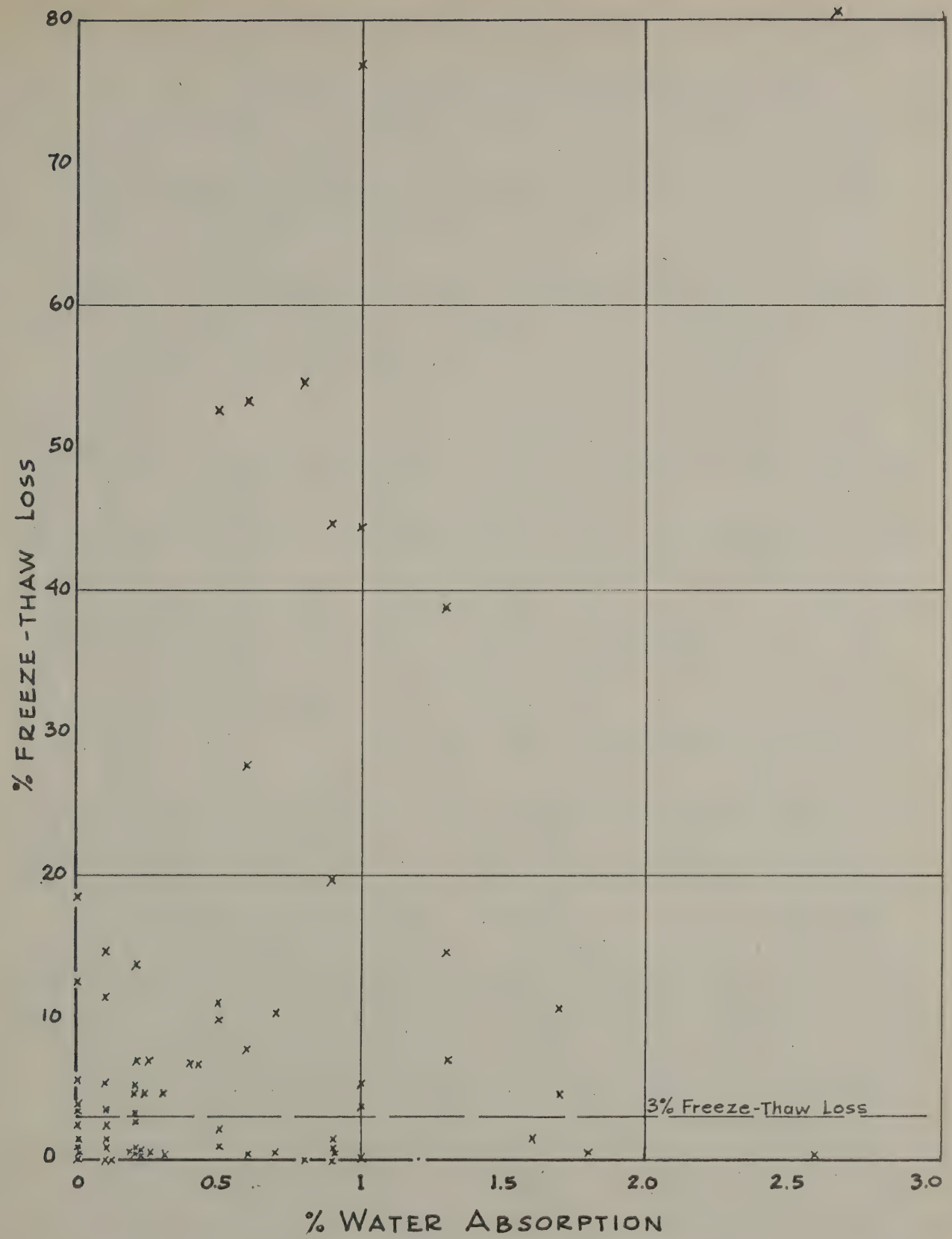



Figure I-13

WATER ABSORPTION VS. FREEZE-THAW LOSS

thaw test loss and 3 specimens with no measurable absorption had over 3% loss. Low water absorption and high loss is very likely caused by minor fractures or stylolitic seams in the aggregate which are too small to absorb enough water to be measured with the equipment used but large enough to absorb a film of water which can freeze and disrupt the rock.

5. Alumina and freeze-thaw loss.

Figure I-14 is a plot of percent of $Al_2O_3$ against percent loss in the freeze-thaw test. High alumina (an indicator of total clay content) and high freeze-thaw are related in a few cases, but the relationship is not consistent. The highest alumina content (over 5.4%) and 8 rocks with alumina contents over 1.0% did not fail the freeze-thaw test.

6. Normative expansive clays and freeze-thaw loss. Of the rocks containing the expansive clays, illite and montmorillonite, 52% had freeze-thaw losses over 3%. Considering that 54% of all carbonate rocks tested had losses over 3%, and had highly variable clay content, it would seem that the presence of normative illite and montmorillonite does not increase the chance of failure.

7. Clay and dolomite.

Figure I-15 is a plot of the percent total clay content against the percent of dolomite in the total carbonate. ▲'s are for the Manlius formation, circles are for the Lockport formation,

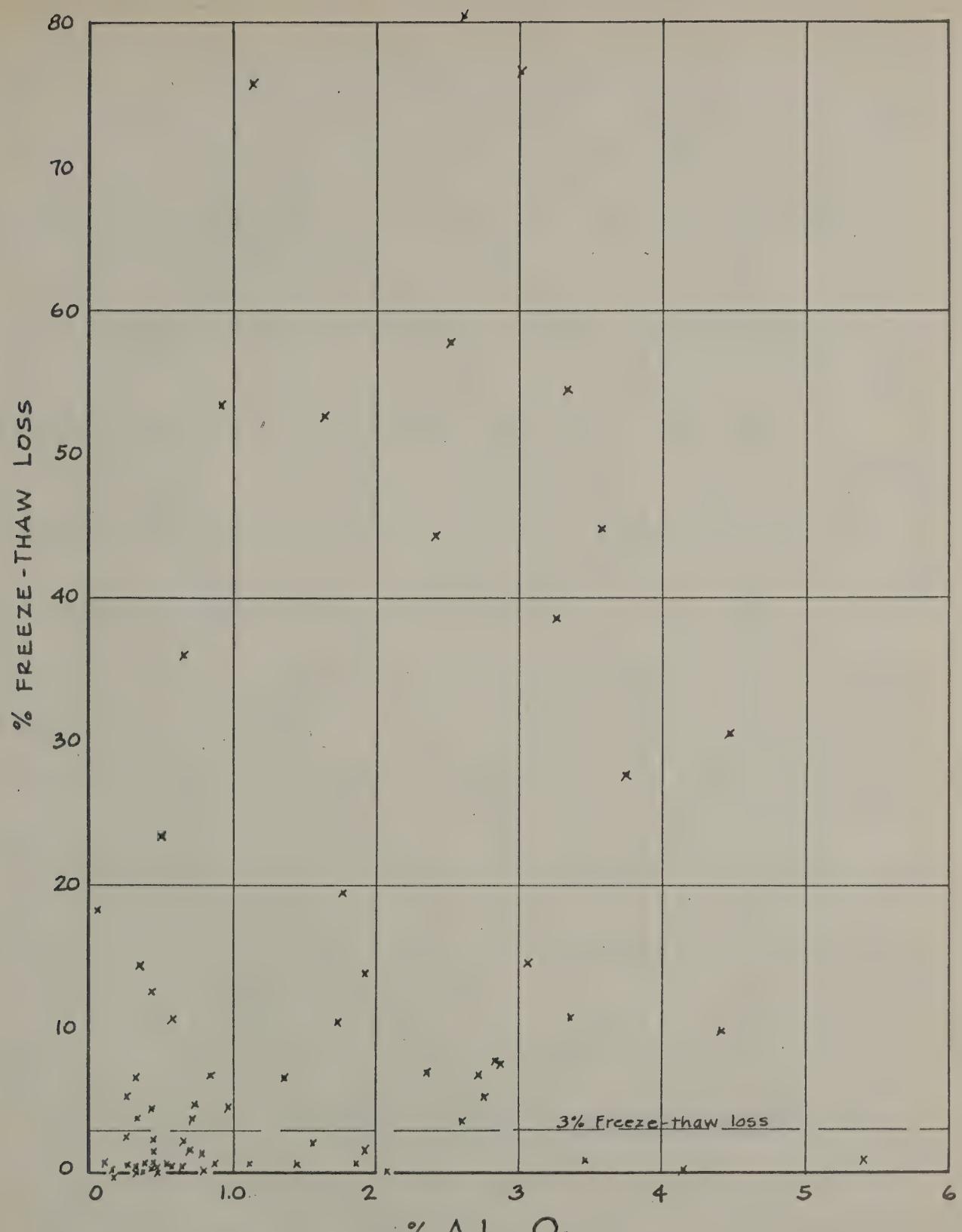
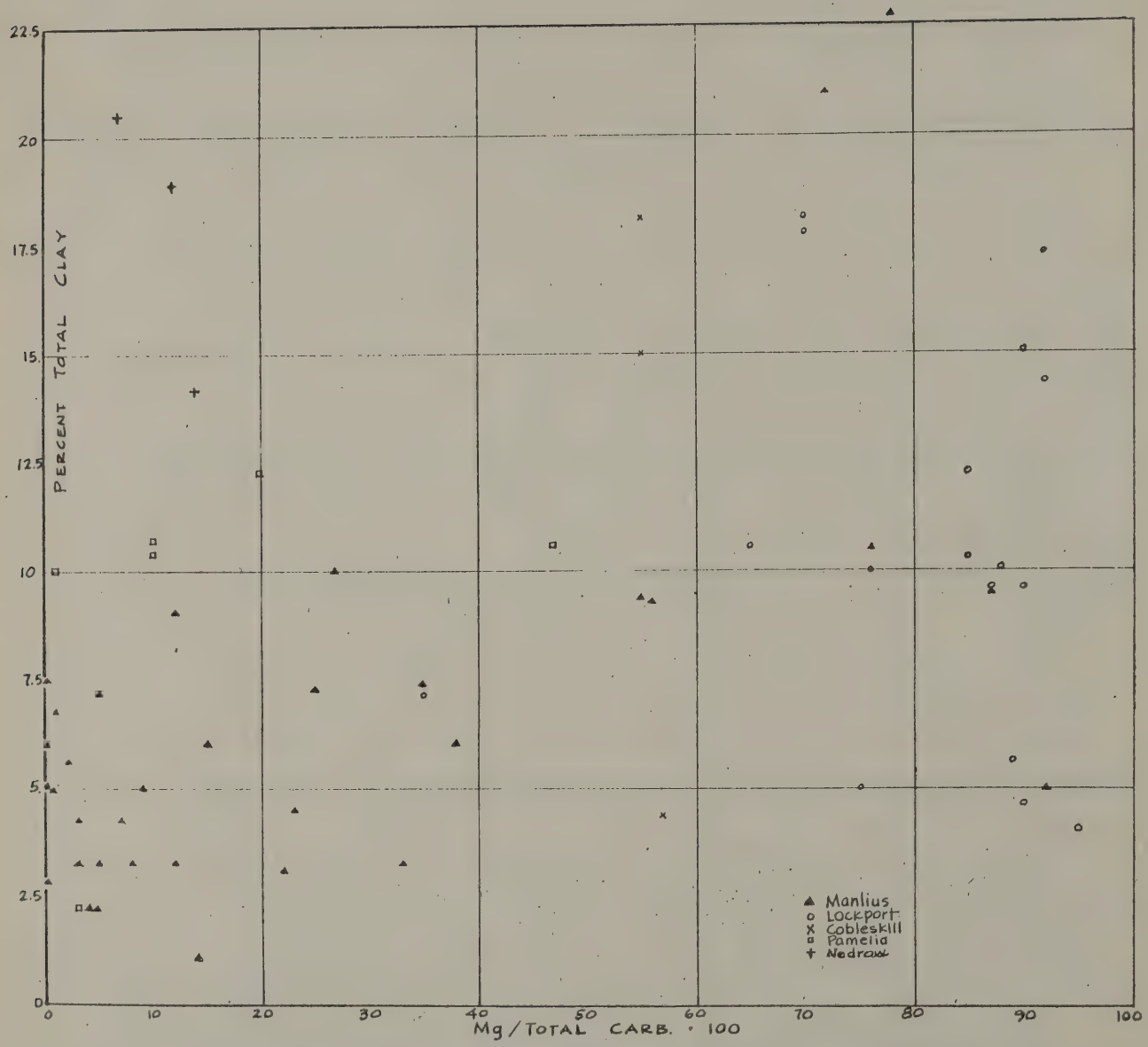



Figure I-14

## $Al_2O_3$ VS. FREEZE-THAW LOSS




TOTAL CLAY PLOTTED AGAINST PERCENT OF DOLOMITE IN CARBONATE

Figure I-15

squares are for the Pamelia formation, X's are for the Cobleskill formation and plusses are for the Nedrow member of the Onondaga formation. The mean clay content for dolomitic formations (Pamelia, Cobleskill and Lockport) is about 10% but for the Manlius limestone the mean is from 5% to 6%.

Dolomitization seems to be favored somewhat by the conditions which favor deposition of clay, i.e. quiet water. By implication quiet water might seem also to favor slower deposition of sediments and therefore dolomitization may also be favored by slow deposition or long contact with sea water.

8. Water absorption and dolomite content.

Figure I-16 is a plot of percent water absorbed against percent dolomite relative to the total carbonate. Although the relationship is not without exception, it is apparent that high porosity is likely to be favored by high dolomite content in carbonate rocks. Figure I-17, % absorption against % dolomite in total carbonate, does not produce any better correlation than in Figure I-16.

9. Water absorption and compressional velocities.

Figure I-18 is a plot of the percent water absorption against the sonic velocity in feet per second. A rough relationship exists between sonic velocity and absorption in that the highest

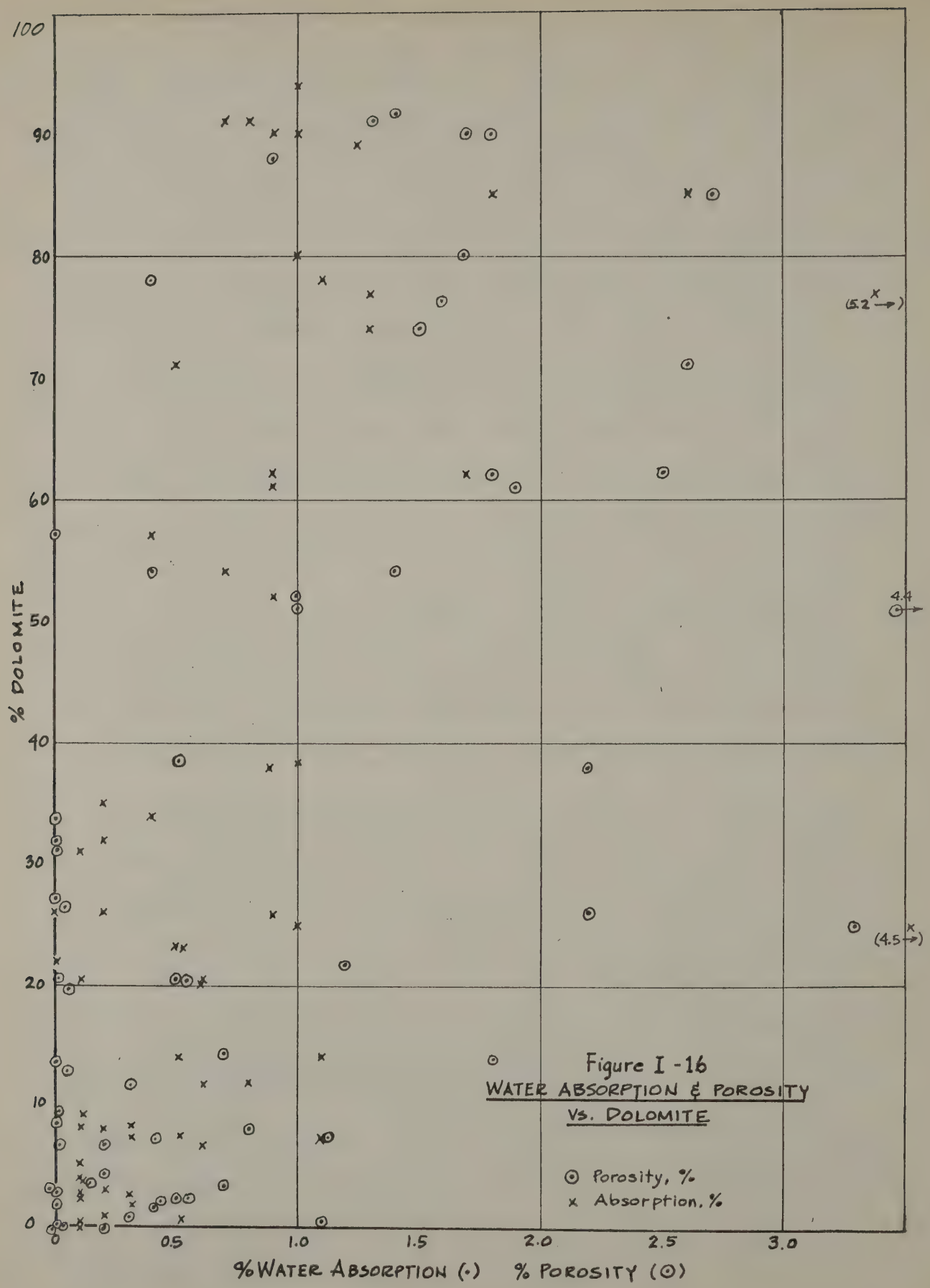



Figure I -16
WATER ABSORPTION & POROSITY
VS. DOLOMITE

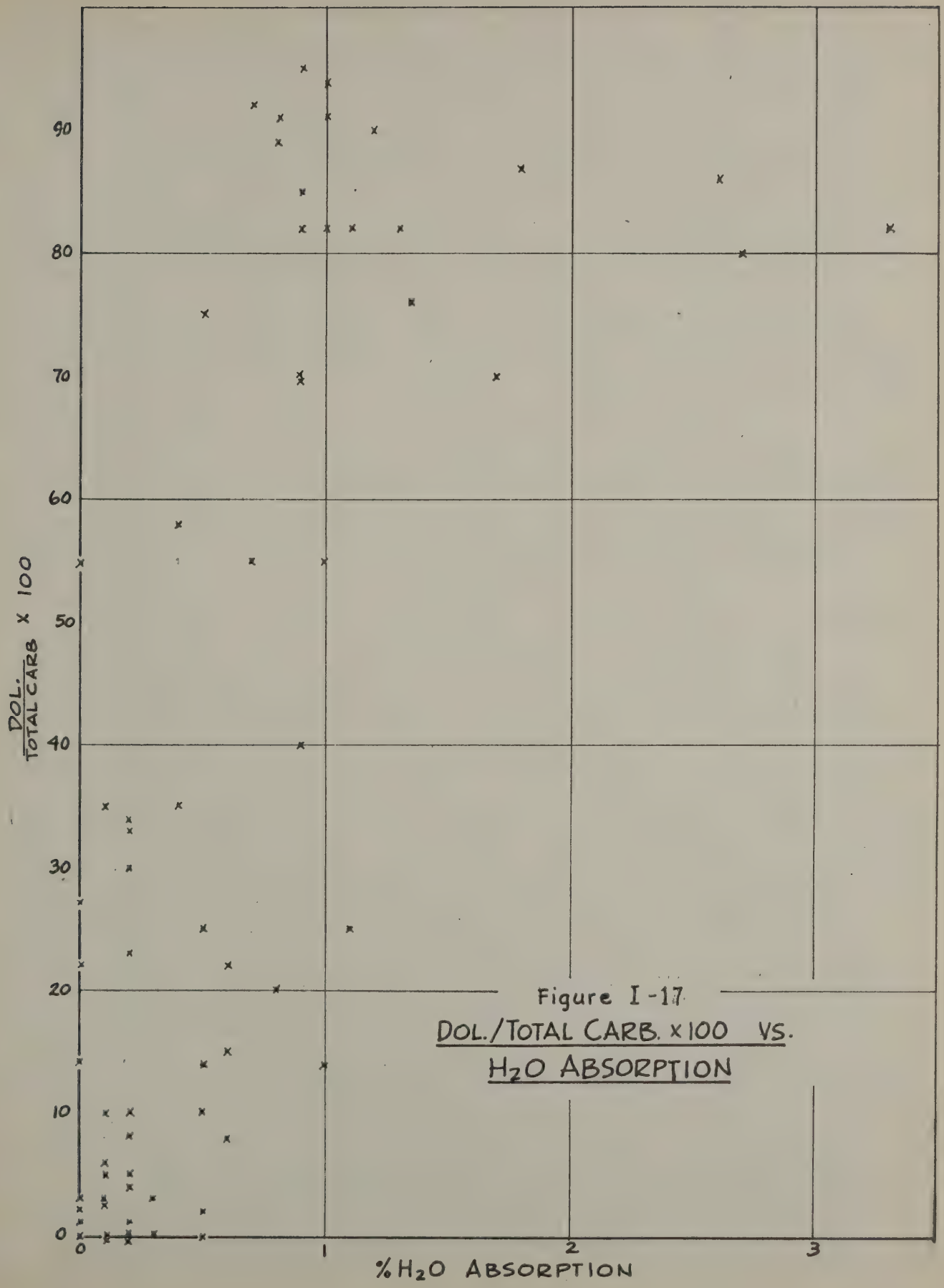



Figure I-17

DOL./TOTAL CARB. x 100 VS. $H_2O$ ABSORPTION

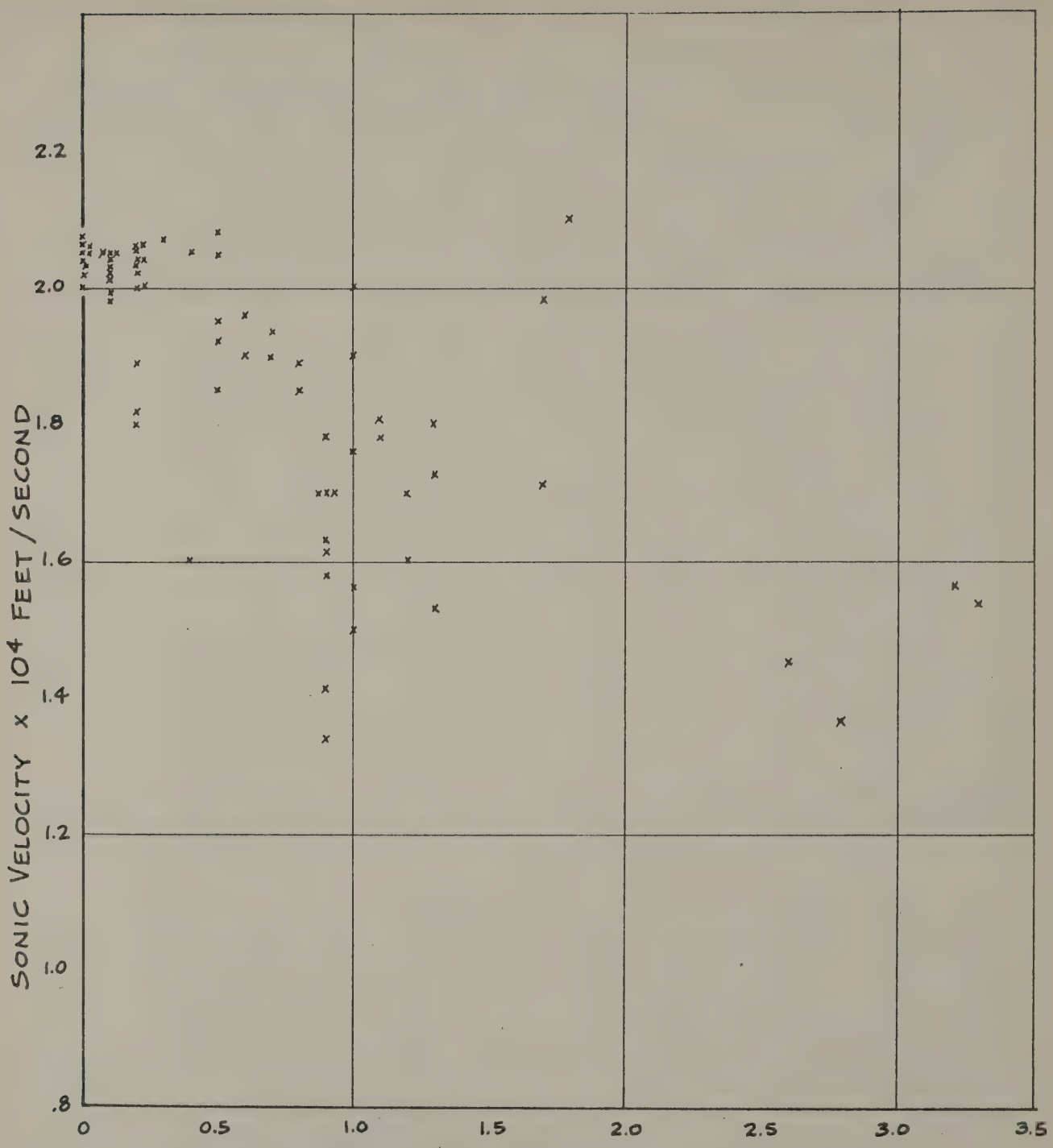



Figure I - 18

% WATER ABSORPTION VS. COMPRESSIONAL WAVE VELOCITY x $10^4$ FT./SEC.

velocities are mostly the least absorptive. Of the ten rocks with average sonic velocities of less than $1.6 \times 10^4$ ft/sec., eight have water absorptions of 0.9% or more.

Sonic velocity is largely a function of density and packing. Pure, tightly packed dolomite should have a sonic velocity higher than limestone because of its higher density but the tendency for dolomite to be porous (also water absorbent) more than offsets the influence of the slightly higher density for the mineral dolomite.

10. Only the most vague relationship could be found between water absorption and clay content, and freeze-thaw loss and percent dolomite.*

Conclusions, Part I:

1. The carbonate rocks of central and western New York are found to cover a wide range of chemical and mineralogic types from almost 100% calcite to 100% dolomite, from sandy carbonate rocks to clay-rich carbonate rocks. Generally the highest water absorptions and lowest compressional wave velocities were found in the dolomitic rocks. Compressional wave velocities vary from 12,600 ft/sec. to 22,500 ft/sec and are largely a reflection of porosity. Neither the clay nor dolomitic contents seem to influence compressional velocities to a great degree.

* Current work at Rensselaer indicates that for freeze-thaw sensitive dolomitic rocks, the % clay associated with dolomite can be correlated with the % water absorption.

2. The theoretical clay minerals are illite, montmorillonite, chlorite, biotite and sericite. Of these, the montmorillonite is the potentially most expansive and most deleterious in concrete, with illite a possible contributor to deleterious reactions. According to normative calculations run on a digital computer several of the carbonate rocks contain what may be significant quantities of montmorillonite and illite. However, X-ray analyses by Kaufman (1963) have verified only the presence of illite, kaolinite and chlorite.

3. Thermal expansion was determined for the range -90°F to +160°F and was found to be essentially a straight line variation. The coefficient of thermal expansion varies from $3.26 \times 10^{-6}$ in/in/°F (a limestone with about 5% normative clay) to $9.07 \times 10^{-6}$ in/in/°F ( a dolomite with about 10% clay ).

4. Two samples showed significant expansion in the dedolomitization test in 1N sodium hydroxide solution, a sample of Pamelia from central New York and a special sample of Beekmantown dolomite from northern New York.

5. Of 80 carbonate samples tested 6 failed in the sodium sulfate soundness test*, 10 failed in the magnesium sulfate soundness test and all which failed the magnesium sulfate soundness test also failed the freeze-thaw test. The average loss for the sodium sulfate soundness test was 1.5%, for the magnesium

*Tests are according to New York State Department of Public Works Specifications

sulfate soundness 4.6%, for the freeze-thaw test 11.7%. Five specimens failed the modified Deval abrasion test for Type B coarse aggregate.

6. Generally speaking the current test limits for the freeze-thaw test seem to be set too low.

7. Of 18 graywacke samples tested, 8 failed the magnesium sulfate soundness test and 15 failed the freeze-thaw test. All which failed the magnesium sulfate test failed the freeze-thaw test.

8. In every case but one of aggregate failure in a magnesium sulfate soundness test the water absorption was over 0.6%. However, in many cases of absorptions over 0.6% no failures occurred.

9. Of the 41 freeze- thaw failures, 17 had water absorptions of 0.0% to 0.44% and with passing sulfate soundness losses. Such freeze-thaw results are not considered significant, because the specimens tested had sharp corners which were easily lost in the test.

10. The freeze-thaw test as applied by N.Y.S.D.P.W. is more severe than the sulfate soundness test, because the average losses of 11.7% for the freeze-thaw tests and 4.6% for the magnesium sulfate soundness test seem disproportionate to the 3% and 10% limits for these tests which are set by the N.Y.S.D.P.W.

11. Low sonic velocities are related to high water absorption and failures in soundness tests.

12. Sulfate soundness test brines do not saturate aggregate under the conditions of the standard tests.

13. The sulfate soundness tests apparently are surficial tests which are used to determine sensitivity of aggregates to the apparent volume effect of freezing and thawing.

14. In preliminary wetting and drying tests of 10 carbonate rocks, three argillaceous dolomites deteriorated badly. No shale was visible in any of the specimens, but normative mineralogic calculations from chemical analyses disclosed relatively high theoretical clay contents (10.62, 11.08, and 12.35%) and 7Å, 10Å, and 14Å, were found in all three samples in routine x-ray analysis. Much more work is needed here.

15. Measurements of water absorption rates at atmospheric pressure and water loss rates in a vacuum disclose that the questionable rocks (known field failures, wet-dry failures and high freeze-thaw losses) have characteristic water gain and loss curves which are easily distinguished from similar curves for satisfactory rocks. It is possible that such curves alone are all that are required to distinguish non-chemically reactive sound and unsound aggregate.

# PART II GEOLOGIC DATA AND STRATIGRAPHIC CORRELATION

## Purpose

The primary purpose of Part II of this report is to present pertinent geologic data and to integrate stratigraphically the mineralogic, physical and chemical data. The heart of the section is the correlation plates* which summarize the stratigraphy and physical and chemical information. A short section in the introduction describes and evaluates the sampling procedures and describes the common causes of variations in rock types which might be expected in layered rocks in New York.

## Continuity of Rock Characteristics

### General Statement:

Fundamental problems in applying the results of any research on aggregate to the practical solutions of quality control in the field are: 1. To relate specific measured values to specific horizons which can be found in the field by competent observers. 2. To determine the degree of lateral and vertical continuity of the various horizons and hence the degree of applicability of the data.

It has not been the purpose of the present report to determine in detail the quality of the rock in each quarry in western New York. Rather, the purpose has been to determine the nature of gross variations of characteristics of the various rock types. However, it is felt that the nature of physical and chemical variations within any particular quarry can be approximately obtained by applying these data to the tested strata. "Typical" samples of every unit

* All plates in pocket in back of report.

at every quarry exposure have been tested and the test figures are probably close to the average for each unit. The statistical reliability of each measurement, however, cannot be determined at this time.

Field Differentiation of Units and Sampling Procedures:

Generally, the first step for determining probable continuity was to describe the stratigraphic units in the field by making stratigraphic logs of quarry faces. On this basis it was possible to make a field differentiation of units which were distinctive in appearance. The intent was to describe and sample all distinctive lithologic units. In some cases the units which were so separated for sampling were new subdivisions of previously described formation members. The fifty pound samples finally selected are believed to be typical of the differentiated layers. The basic premise which justifies this method of selection of samples is that a layer which appears the same at every exposure to competent observers over a given area is probably also similar in its physical and chemical characteristics over that area. One obvious shortcoming is that the competency of the observer determines his ability to pick distinctive layers. To a completely untrained observer all layers may "look alike," but to a well-trained observer a given stratigraphic interval may contain many well defined lithologic types. Ordinarily, the most competent observers see the largest number of distinct layers.

It is felt that more subdivisions of the rocks in question can be made than were noted in this report, but limitations of time and money restricted the number of samples. Meanwhile, if future stratigraphic differentiation is done in more detail than in the current work, the samples which have been studied can be integrated readily, because their positions have been precisely located on stratigraphic sections.

In most cases, a given layer of rock over the area of a quarry is very similar in its physical, chemical and lithologic characteristics. An example of the extreme continuity which rock layers can have has been described by Dunn (1961), who noted that the individual layers of the Manlius, Coeymans and Kalkberg formations over about a square mile varied less, compositionally, than the analytical error in the testing laboratories. In fact, the compositional characteristics which serve to differentiate the individual layers (as thin as 2-½ feet) in the Manlius, Coeymans and Kalkberg do not change appreciably from South Bethlehem to Kingston, a distance of nearly 50 miles.

Generally, geologic formations, members and individual strata, maintain a compositional identity, and physical tests run on a single properly taken sample of a given layer from a quarry property are enough to determine that layer's characteristics over the whole property. The samples taken for the present report, as indicated before, are not ideal for rigorous testing of a layer, because such testing should be done on the whole interval, not a block which is theoretically representative of the interval.

In the author's opinion ideal samples consist of cores, 2-1/8 inch in diameter or greater, which are subdivided into sample intervals which are representative of all traversed lithologies. Such sampling should be done on several logged and correlated cores to average normal experimental and sampling errors.

Causes of Variations within Layers:

An individual rock layer may change in appearance and in other measurable characteristics for several reasons, some of which are described below:

1. Weathering. At the top surfaces, along fractures such as faults or joints, and around caves, rocks tend to weather. How much a rock is altered by weathering is determined not only by the exposure but by the character of the rock itself. A dense non-argillaceous limestone tends to dissolve at the surface so that the weathered material is carried off in solution. Dense, pure dolomites are similar. However, calcareous dolomites or dolomitic limestones tend to weather very differentially because the calcite is much more soluble than dolomite and is dissolved away tending to leave a loose, porous mass of poorly cemented dolomite crystals. A sandy limestone, sandy dolomite or a sandstone cemented with carbonate minerals are similar, but the friable mass remaining is largely quartz instead of dolomite. Shaly rocks also weather preferentially so that the shale layers weather back and the harder zones (carbonate layers or graywackes in the present research) stand out in relief.

Argillaceous rocks, in which the clays are disseminated, may or may not weather easily. When the clay is enclosed in individual crystals, as in the New Scotland limestone, or when the clays are not expansive, as in the Catskill graywackes, the rock may weather slowly and tend to outcrop. However, if the clay is expansive and distributed at the boundaries of carbonate crystals, for example, the dolomitic Thacher and the "C-unit" of the Lockport, the rocks tend to break down quickly due to wetting and drying and/or freezing and thawing in quarry faces and also do not outcrop in nature (for a fuller discussion of this phenomenonsee Part III of the present report and Kaufman, 1963).

The Catskill graywackes are a special problem. They are highly argillaceous and it seems reasonable that they should decompose rapidly during weathering. However, most of the Catskill graywackes outcrop prominently and form cliffs. Talus blocks below cliffs have sharp edges indicating freeze-thaw soundness. The lack of sensitivity to weathering may be caused by the nature of the clays. According to Miller and Senechal (1962, pg. 9): "The data definitely indicate the absence of any clay that expands on hydration."

2. Reefs. Limestones and dolomites commonly contain coral or algal reefs. Generally the reefs are discontinuous, lenticular zones of carbonate which may be from inches to hundreds

of feet thick and may be high and steep-sided or broad and flat. Reefs in the Onondaga formation are porous, weak carbonate layers which are broadly lensoid. The C-layer in the Lockport formation consists largely of reefs and the weathered debris between reefs. Reefs in the Manlius limestone in eastern New York replace some rock layers locally and cause a change from bedded limestone to massive limestone.

Reefs generally cause an increase in porosity, an increase in carbonate content and probably a decrease in sonic velocities. Reefs are usually easily distinguishable from other lithologies, so that the change in characteristics is predictable from normal geologic description.

3. Faulting, Faults and accompanying shear zones may cause radical physical changes in the rock they traverse. Such rocks are likely to be severely fractured or likely to contain closely spaced zones of weakness which may cause the rocks to deteriorate rapidly in nature and in laboratory tests. Faults and shears are generally readily observed by noting displacement of beds, broken zones, evidence of sliding, deep weathering, or other commonly noted geologic criteria.

4. Metasomatic changes. Rocks are frequently replaced along zones of permeability such as faults or other openings by new minerals. Limestones, in particular, may be replaced by many minerals, most commonly silica and dolomite. In the Hudson

Valley solutions moving along faults have caused limestones to change to dolomites. Such changes are easily detected because of differences in hardness, texture and/or color. Changes from limestone to dolomite may be accompanied by loss of soundness. Silicification along faults or shears is not common in New York and dolomitization along faults has not been observed to have occurred in western New York.

5. Broad Changes along Layers. Slow changes of individual beds, formations or members occur laterally along nearly all rock units. Limestones or dolomites may grade into shales as in the Lockport formation east of Syracuse, or sandstones to shales as at the Western periphery of the Catskill graywackes. Such lateral changes are seen in the stratigraphic correlation charts for the Onondaga formation (Dunn and Ozol, 1962), and for the Lockport formation, see Plate II-3A.

Changes of this nature generally are gradational and require miles before their nature is clear. An area the size of a quarry property is usually too small for such changes to be observed. However, in some cases, abrupt changes do occur. For instance the Little Falls dolomite changes from sandy, conglomeratic material against the exposures of Pre-Cambrian Adirondacks (crystalline rocks) to dolomite a few hundred yards away from the exposures.

Causes of Variations from Layer to Layer:

Bed to bed variations such as graywacke to shale in the Catskill graywackes and limestone-dolomite oscillations as in the case of the Pamelia formation are exceedingly common. Such changes reflect the constant dynamic changes in depositional environment such as depth of water, rainfall variations, abundance of fauna, composition of the sea and many other factors. The nature of some of the more critical environments is discussed below, as they concern rocks studied in the present project. The more speculative aspects of the variations are not discussed.

1. Dolomite. Nearly all carbonate rocks contain at least a small amount of magnesium which tends to segregate into dolomite crystals. However, under some conditions (not well understood at present) limestones or limey layers are replaced, apparently during or shortly after compaction, by dolomite because of reaction with sea water or other aqueous solutions. Slight changes in the composition of sea water or perhaps prolonged exposure to sea water may cause these changes. The suggested chemical reaction is:

Calcite Dolomite

$$2CaCO_3 + Mg^{++} = CaMg(CO_3) + Ca^{++}$$

The dolomitic rocks herein described were formed by such sedimentary processes. This change is accompanied by a 12.6% decrease in volume and may be largely responsible for the higher porosities in dolomites relative to limestones.

(Because compaction of sediments usually occurs during dolomitization, the porosities are generally far less than the 12.6%)

2. **Chert.** The nodular bedded cherts which occur in limestones and dolomites are replacements of the carbonates by silica. The general situation is similar to the process of dolomitization in that silicification occurs probably on the ocean bottom after or during lithification. Ozol (1963) observed that some chert nodules have stylolite boundaries (zig-zag lines of weakness common to most carbonate rocks) in the Onondaga limestone, suggesting that they originated after solidification or after crystallization of the carbonate. Chert in the Little Falls dolomite in New York State was formed before the dolomite, judging from the replacement relations, but some cherts are deposited after dolomites. The Onondaga formation is the only unit described in this report in which this sort of silicification is common.

3. Limestones. Limestones are generally deposited in shallow seas as lime muds or fossil accumulations or both. For instance, the Lowville limestone contains mud cracks indicating that it was deposited as a lime mud in a mud flat. The reefs, which are so common in limestones, also indicate shallow deposition.

4. Shale and Clay. Clay is generally deposited in more quiet water and frequently in deeper water than limestones. Variations between limestone and shale largely represent variations in depth of water during deposition. The Catskill graywackes are argillaceous sandstones in which clay, silt, sand and mud balls were deposited together, apparently dumped on a river delta. Sinuous shale lenses apparently represent channel fillings on the surface of the Catskill delta but the continuous shale layers suggest temporary local submergence or ponding of the delta. The abundance of clay in some limestones is caused by relatively quiet depositional conditions.

5. Sandstone and Sand: Sand is most generally deposited under conditions of moderate water agitation such as along a fairly active sea shore or on a river delta. Sandy limestones and dolomites, such as part of the Lockport dolomite and part of the Pamelia, indicate deposition in a fairly shallow sea where there was enough velocity of movement of current to move sand grains. Most free silica in the normative analyses of the carbonate rocks described in this report is quartz sand or silt (the major exception to this is the free silica in the Onondaga formation which is mostly chert).

## NEDROW MEMBER OF THE ONONDAGA FORMATION (3 SAMPLES)

The name Nedrow is given to the argillaceous limestone lithology which is stratigraphically above the Edgecliff member and below the Moorehouse member of the Onondaga formation. Eight feet of Nedrow are exposed at Munnsville; it is 22 feet thick at Syracuse, 25 feet thick at Seneca Falls, 18 feet thick at Phelps and 11 feet thick at Avon. It pinches out west of Avon.

The part of the Nedrow member which was studied in this report is the most argillaceous portion. This is the lower 13 feet at Seneca Falls and the whole exposure at Phelps and Avon, New York.

The clay-rich Nedrow consists of interbeds of fine-grained, medium dark gray* to dark gray limestone fresh (lighter gray to buff weathering), medium-grained, argillaceous limestone which contains less than 1% brownish gray chert. Indistinct bedding planes are 5" to 6" apart. Locally 6" to 12" relatively pure, limestone layers with coarser texture are visible. The clay and silty material are disseminated and not obvious on a fresh surface, but prolonged weathering leaches out the calcite and leaves an argillaceous paste.

The samples tested for the present report are the argillaceous zones and are not representative of the whole Nedrow.

Chemical and Mineralogic Characteristics:

The Nedrow is a dolomitic limestone which averages about 10% dolomite and nearly 70% calcite with a moderately high clay content of 13% to 21% and a low (for Onondaga) free silica content of 2% to 6%.

*Colors are carefully defined by hue and chroma according to the Rock Color Chart, Geol. Soc. Am., 1951.

Physical Characteristics:

The Nedrow member is apparently fairly constant in its water absorption (0.5% to 0.6%) but variable in its porosity as determined from specific gravities. All specimens of Nedrow failed the freeze-thaw according to the established N.Y.S.D.P.W. test limits but were satisfactory on other tests. All specimens had only moderate sonic velocities, varying between $1.67 \times 10^4$ ft/sec. to $1.94 \times 10^4$ ft/sec.

It seems likely that the Nedrow member of the Onondaga is not an extremely high quality rock but should generally be satisfactory in service.

# MANLIUS FORMATION

## Introductory Statement

The Manlius is the oldest formation in the Helderberg group of Devonian age in central New York. The formation is divided into five units (oldest to youngest): the Thacher, Olney, Elmwood, Clark Reservation and Jamesville members. All units of the Manlius formation are presently being quarried in central New York, thus providing good stratigraphic control.

The Thacher member extends from DeWitt westward to the Hudson Valley where it is the only member of the Manlius formation represented. The Olney member is present from Auburn, New York, eastward to the Sangerfield quadrangle where it grades into the Dayville member of the Coeymans formation (Rickard, 1962). In the same manner the Elmwood, Clark Reservation, and Jamesville members extend eastward into the Richfield Springs quadrangle where they also grade by facies change into the Ravena member of the Coeymans formation (Rickard, 1962). The Manlius formation is conformable on the Rondout magnesian limestone formation (late Silurian or early Devonian) and is overlain by the Coeymans limestone formation of the Helderberg group. The type section of the Manlius limestone as described by Smith, et al, (1929) can be most easily seen in the quarries around Manlius, New York. The stratigraphic divisions of the Manlius which are used here are according to Rickard (1962).

Thacher Member (3 samples)

The Thacher member of the Manlius formation lies conformably on the Rondout formation and at DeWitt, near Syracuse, is gradational into the Rondout. Rickard (1962) places 20 to 30 feet of what were formerly called Rondout and Olney into the Thacher. The top of the Thacher is taken as the top of a 3 foot bed of light gray, buff weathering dolomite. Two similar beds of dolomite occur in the area; a 14 inch bed 11 feet below the base of the upper dolomite, and a 4 inch bed 8 feet below that. Between the dolomites the lithology is typical fine grained, dark gray, medium bedded, fossil-poor Manlius similar to the Olney.

Chemical and Mineralogic Characteristics:

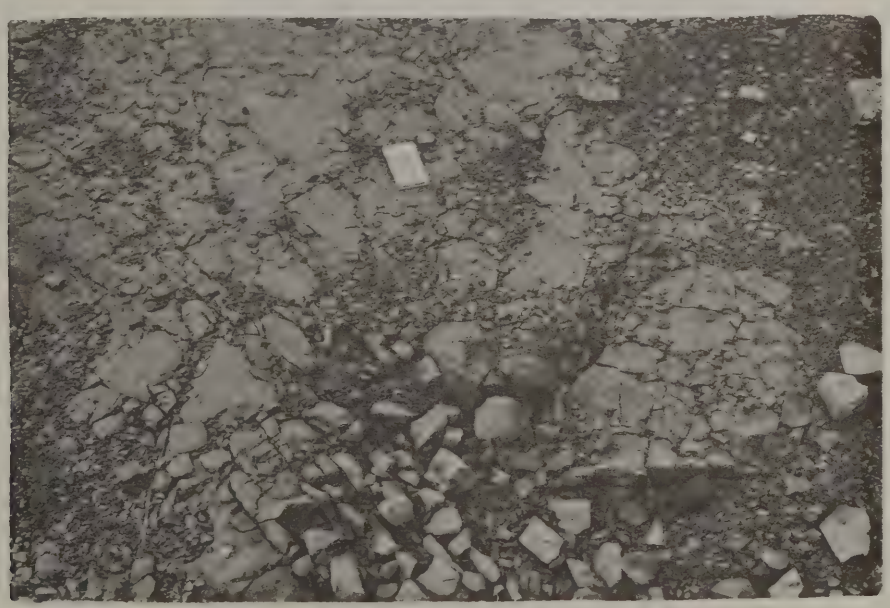
The predominent, dark gray Thacher (Sample RB) is typically a dolomitic limestone which is 93% carbonate, with a dolomite content of 56%. Clay and a small amount of free silica are the minor constituents. The lighter col red dolomite layers (RA and OD) are more argillaceous and are from 72 to 76% dolomite and 78 to 80% carbonate.

Physical Characteristics:

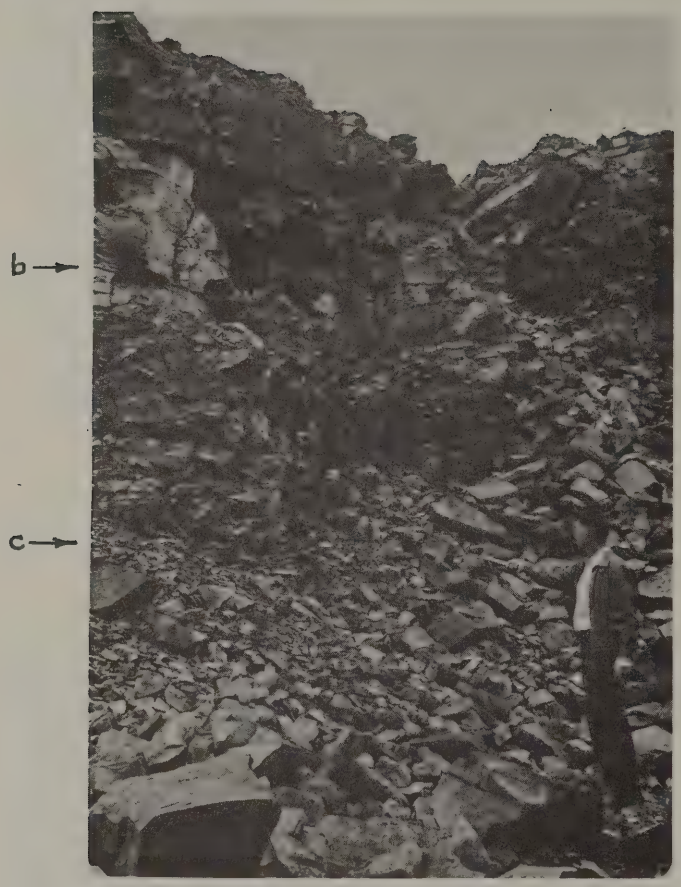
The dolomitic limestone layers are characterized by fairly high sonic velocities, have moderate soundness losses and water absorptions. The samples of light colored dolomite which were tested have low sonic velocities, high porosities, and fail the freeze-thaw test. In the quarry at DeWitt it is obviously sensitive to weathering, decomposing

by conchoidal fracturing on weathering. The lower light gray dolomites in the Thacher weather similarly. Photographs II-1 to II-3 show the weathered dolomite layers and their relationship to the adjacent more sound layers.

Photograph II-1. Upper argillaceous dolomitic Thacher member of the Manlius formation, DeWitt. Note the conchoidal fracturing of the buff-colored dolomite indicating unsoundness.



Photograph II-2. Dolomite Thacher member of the Manlius formation. Photograph taken 11' below layer in Photo II-1. Note weathering unsoundness.




Photograph II-3. Thacher member of the Manlius formation, DeWitt. The three badly weathered argillaceous dolomite layers are indicated at a, b, and c with apparently sound rock between.

Olney Member (6 samples)

The Olney member is a laminated to massive-bedded, medium to coarse grained, carbnn-rich limestone which weathers to a gray-brown and is medium gray on fresh surface.

Generally fossils are not readily observed, but locally beds exhibit well-preserved crinoid stems and reef debris, especially in the quarry at Paris (Quarry 2-7R). Chert nodules and irregular shale stringers constitute up to 2 percent of the exposed Olney limestone at Paris.

The lower contact of the Olney member with the Thacher member is taken as the top of the light gray dolomite bed (3 ft. thick) at DeWitt. The Thacher at DeWitt was formerly called Olney but the change to "Thacher" by Rickard (1962) seems to be more realistic.

Contact with the overlying Elmwood-A submember is sharp, the Elmwood usually exhibiting a coarser grained texture. Characteristics which separate the Olney member from the Elmwood member are slabby bedding, general absence of fossils, and shaly zones containing sparry calcite lenses. The thickness of the Olney member is 35 feet at Marshall (Quarry 2-9R), and represents the most complete exposed section in the Syracuse area, although the lower contact with the Rondout formation is not exposed.

Chemical and Mineralogic Characteristics:

The Olney limestone member averages 7% dolomite, 3.5% normative silica, 4.6% normative clay and 6.5% total insoluble residue.

Physical Characteristics:

The physical characteristics exhibited by this member include an average compressional wave velocity of $2.0 \times 10^{4}$, true specific gravity of 2.71, coefficient of thermal expansion of $4.0 \times 10^{-6}$ and average water absorption of 0.7%. One sample (OZ) failed the freeze-thaw test with a loss of 36.5%. Samples 24-OL and R-2, with losses of 4.5% and 6.6%, also failed, but the failures are not believed to be significant for reasons indicated in Part I*.

* As indicated in Part I the large number of freeze-thaw test "failures" (54% of the rocks tested in the present research) does not correlate with field failures, because most of the rocks studied have excellent records. In addition, the average freeze-thaw test loss for the rocks tested is 11.7% compared with 4.6% for the magnesium sulfate soundness test; however, the maximum loss acceptable for stone used in portland cement concrete is 3% for the freeze-thaw test and 10% for the magnesium sulfate soundness test, the opposite of what might be anticipated. Considering the virtually identity of each pair of samples which were tested and are being compared, it seems evident that the present acceptance level for the freeze-thaw test is too low. From 10% to 20% maximum loss would be more realistic.

Elmwood Member (13 samples)

The Elmwood member is divided into three sub-members, A, B, C, in ascending order.

1. The Elmwood A submember (3 samples) is a dark gray fresh, yellow-buff weathering, argillaceous, fine-to-coarse-grained, laminated to slabby-bedded limestone with reef layers and associated reef debris sparsely distributed in limited beds. Well preserved crinoid stems are found in Quarry No. 2-7R. The unit varies in thickness from 2-9 feet and is chemically and mineralogically variable.

Chemical and Mineralogic Characteristics:

The total carbonate is about 90% but may contain from about 1% to 31% dolomite. Silica is typically about 5%; total clay about 3-16%; insoluble residue 6 to 10%.

Physical Characteristics:

Typical physical characteristics include compressional wave velocities of about $2.00 \times 10^4$ feet/sec., true specific gravity of 2.72, and water absorption less than 0.22%. Only one sample failed any one of the soundness tests (sample #34-EA-6.86% freeze-thaw loss), but it is not considered to be significant for reasons previously noted.

2. The Elmwood B Sub-member (4 samples) is a dark-gray shaly, argillaceous, reefoid, slabby to medium-bedded limestone with abundant reef debris, and isolated, clear calcitic masses. It weathers to a medium-light gray.

Chemical and Mineralogic Characteristics:

The Elmwood B is 84 to 92% total carbonate (0-8 % dolomite), has 5 to 8% clay, 3 to 6% silica, and averages about 9 to 10% insoluble matter.

Physical Characteristics:

The Elmwood B is characterized by an average of $2.03 \times 10^{4}$ feet/ sec. compressional wave velocity, 2.72 true specific gravity and water absorption of less than 0.21%. The average coefficient of thermal expansion for sample E-2 is $3.37 \times 10^{-6}$. Samples E-2 and 26-EB failed the freeze-thaw test with losses of 5.2% and 14.6% respectively but passed all other soundness tests. The freeze-thaw failures are not considered to be significant.

3. The Elmwood C sub-member (6 samples) is a fine-to-medium-grained, laminated, argillaceous, medium-dark gray, dolomitic limestone with occasional shaly partings. It weathers to yellowish gray color. This unit varies in thickness from 4 to 10 feet.

Chemical and Mineralogic Characteristics:

The chemical characteristics which distinguish this member from other sub-members is its high dolomitic content (18% average). It averages 83 to 97% total carbonate, 3 to 14% total clay and 1 to 4% free silica.

Physical Characteristics:

Physical characteristics include variable compressional wave velocity from 1.52 to 2.25 X $10^4$ feet/sec., 2.75 true specific gravity, variable water absorption, from 0.0 to 0.9% with the most dolomitic layers the highest, and a coefficient of thermal expansion for two samples of 5.57 to 6.89 X $10^{-6}$. Samples 42-ECX, R-1-1, 34-EC, and 24-EC all failed the freeze-thaw tests and 24-EC also failed the sodium and magnesium sulfate tests. The failures of the Elmwood C sub-member sample 24-EC (Quarry 2-7R) are believed to be significant. Of special significance may be other characteristics of samples R-1-1 and 24-EC. Both have significant water absorptions, high specific gravities, high coefficients of thermal expansion, low sonic velocities, high dolomite content, and failure in at least one of the soundness tests. In some respects sample 34-EC shows some of the characteristics mentioned above. All of these samples are stratigraphically from the same position in upper Elmwood C sub-member.

Clark Reservation Member (7 samples)

The Clark Reservation member is a fine-grained to sub-lithographic, laminated, gray to pale yellowish brown limestone, weathering to a buff surface. Dolomite stringers and lenses surround argillaceous patches in the lower part of the member. The unit varies in thickness from 2 to 7 feet.

Chemical and Mineralogic Characteristics:

Typical chemical characteristics include low dolomite content (except for bottom portions of member), 3 to 16% total clay, 0 to 11% free silica content, and a low total insoluble content except for lower portions of member. The carbonate varies from 79 to 96%, with the dolomite content very low in the upper parts and moderate at its base where it is in contact with the magnesian Elmwood C.

Physical Characteristics:

Typical physical characteristics include true specific gravity 2.71, compressional wave velocity of $2.07 \times 10^4$ feet/sec., variable percent water absorption (low in upper sections of member, 0.2%; higher in lower portions of member, 0.6%) and coefficient of thermal expansion of $4.2 \times 10^{-6}$. Sonic velocity and coefficient of thermal expansion values seem to indicate homogeneity in the middle and upper portions of the Clark Reservation member. Samples OL-1-1, CR and 26CR had freeze-thaw test losses of 2.5%, 12.4% and 76.8% respectively.

Jamesville Member (11 samples)

The Jamesville member is a fine-to-medium grained, laminated to massive bedded, gray-blue limestone. Stylolitic partings are abundant and give the bedding planes an irregular character. A common characteristic of this member is the presence of stromotoporoid reef which, in outcrop, look much like cabbage heads. Weathering produces light-gray to buff surfaces. Dolomitic lenses are discontinuous and infrequent. The thickness of the Jamesville member varies from 29 feet in Quarry 3-3R to 9 feet in Quarry 2-7R. However, the complete section in the latter quarry is not represented because the top has been eroded. In general the Jamesville thins from west to east, accompanying a reduction in the percent of biostromes in the section.

Chemical and Mineralogic Characteristics:

Typically the Jamesville is less than 6% total clay, less than 1% free silica, and has a variable dolomite content, from 0.0 to 35%. Three samples had high dolomite contents (13 to 35%) whereas 4 samples had less than 1% dolomite. The total carbonates are from 88 to 96%.

Physical Characteristics:

Typically, physical characteristics are: average compressional wave velocity of about $2.02 \times 10^{4}$ feet/sec., coefficient of thermal expansion 2.70 to $3.71 \times 10^{-6}$, true specific gravity of 2.70 to 2.73 and less than 0.27% water absorption. Five samples failed the freeze-thaw soundness test but most of the failures are believed to be too low to be of significance.

Cobleskill Calcareous Dolomite Formation (3 samples)

At its type section, the Cobleskill (upper Silurian) may be divided into two parts. The lower portion, 4 feet thick, consists of massive, fossiliferous beds composed of dusky-blue limestone of medium grain. The upper portion is 5 feet thick and much more thinly bedded and fossiliferous. It is a fine-grained, mottled limestone grading upwards into a dolomite limestone with a tendency to fracture conchoidally. The upper portion apparently persists throughout the predominantly limestone area and becomes dolomite to the west. At Chittenango Falls the barren dolomite completely replaces all limestone strata. West of Chittenango Falls the Cobleskill has a massive basal layer and contains abundant stylolites, and the fine-grained brownish dolomite weathers to a yellow-brown color. At Quarry #4-8R where the specimen was collected, it unconformably underlies the Onondaga (see Figure II-1).

K-3-b and K-2 are taken from the massive, irregularly bedded mottled and vuggy upper part, while K-3-a is from the normally bedded lower part.

Chemical and Mineralogic Characteristics:

The three samples of Cobleskill formation fit a relatively narrow pattern of chemical and mineralogic characteristics. The total carbonate is between 83% and 93% with the dolomite content about 62% of

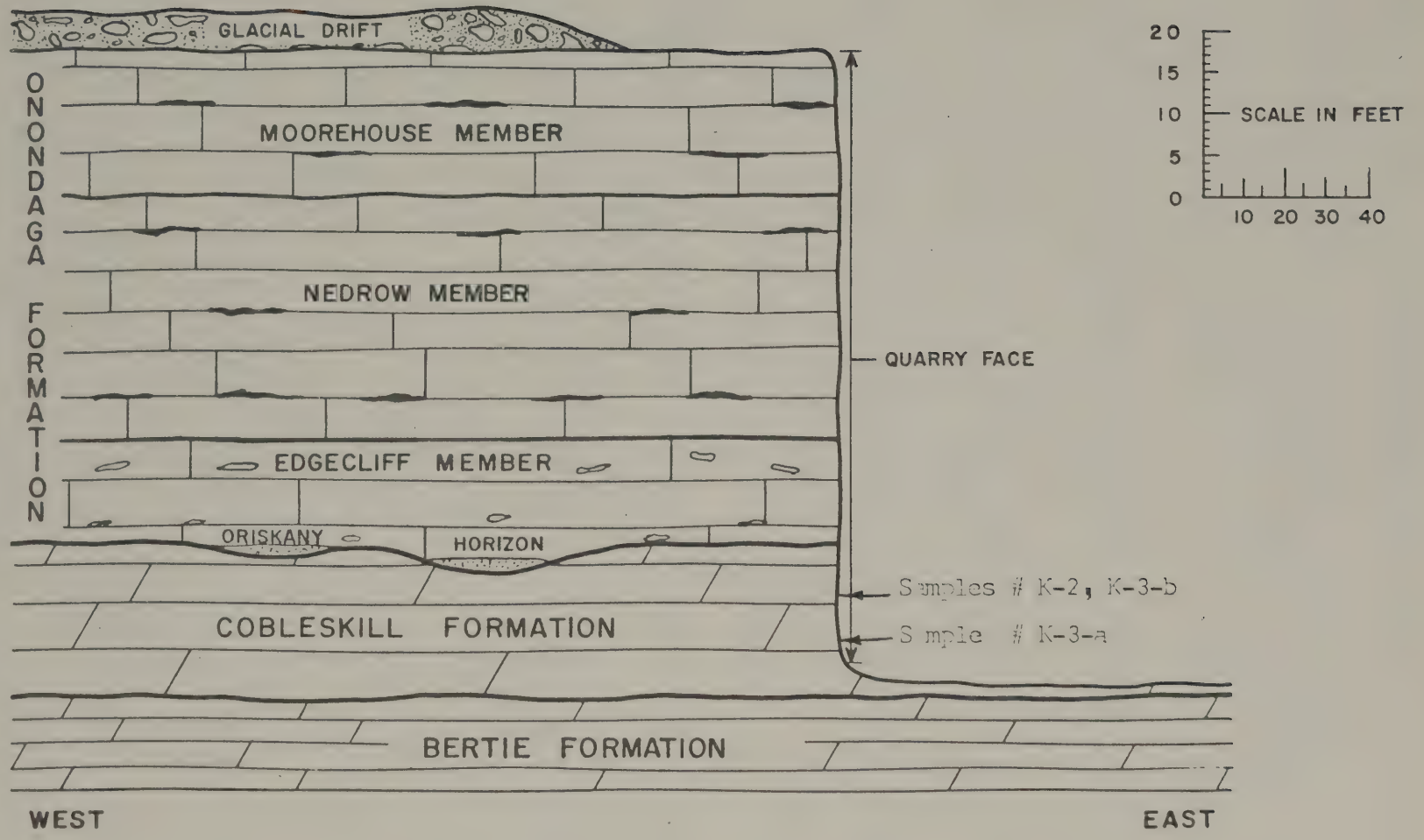



Figure II-1

QUARRY NO. 4-8R

After N. Y. S. D. P. W. Research RR 61-3

the total carbonate. The free silica content is uniformly less than 1.94%. The insoluble residue is from 7% to 12% with the normative clays are unpredictably variable in species.

Physical Characteristics:

The specific gravity (2.75) of the Cobleskill formation is about as would be anticipated from the dolomite content, and the high sonic velocities (1.95 to 2.11 X $10^4$) indicate that the carbonate grains are dense and well packed. The coefficient of thermal expansion for sample K-2 of 7.43 to 7.92 X $10^{-6}$ is about as would be anticipated from the dolomite content. The water absorptions of 0.1 to 0.7% are low considering the dolomite content and the Deval, sodium sulfate and magnesium sulfate tests are all very low. All three samples tested failed the freeze-thaw test, 3.6 to 10.2% loss, but in view of the uniformly high quality indicated by other measurements, the freeze-thaw failures are not believed to be significant.

## LOCKPORT FORMATION

### Introductory Statement

The Lockport formation (previously referred to as the Lockport dolomite) was not studied systematically until Zenger (1962) who studied its lateral and vertical variations and faunal and petrographic characteristics. The units which are used in this report are basically defined according to Zenger with some modification for the special purposes of this paper. Plate II-3 A is a summary of the stratigraphic units, sample numbers, quarries and their locations which were studied.

### Decew Member (4 samples)

The basal unit of the Lockport is the Decew. Fisher (1959) considered the Decew as a separate formation but Zenger assigns the Decew to the Lockport. The Decew is named for exposures at Decew Falls, Ontario, of a fine-grained, grey-weathering, argillaceous dolomite overlying the Rochester shale and underlying the Gasport member of the Lockport. The unit extends from Ontario into New York State as far east as Rochester. From Rochester to Marion the Decew disappears and its stratigraphic position is occupied by the Gates dolomite.

The Decew is about 8 feet thick at Niagara Falls and increases to 15 feet in the Lockport-Rochester area. The top of the Decew is a relatively pure dolomite while the lower is little more than a dolomitic shale; therefore, its petrographic, physical and chemical characteristics

vary considerably from bed to bed. The following description is of specimen 2a, 5 feet from the top of the Decew at Lockport, New York (Quarry 5-5R): Dolomite, fine-grained (0.1 to 0.5 mm), light-gray to medium gray with scattered, irregularly shaped patches of greenish-gray very fine-grained dolomite. Slight evidence of stratification indicated by darker colored layers about 2mm. thick. Weathered samples are a distinct dead-gray color.

Chemical and Mineralogic Characteristics:

Normative analysis indicates that specimen 2a consists of 81% carbonate which is 75% dolomite and 25% calcite. There is 6.5% quartz and 11% clays which are dominantly chloritic. A Decew sample from the same location was studied by Mahdi Mohammed (1963) (DQ-1-1) who found 87% total carbonate consisting of 80% dolomite and 20% calcite, 4% quartz and 5% clays which were mostly illite. Mohammed's DQ-1-1 sample came from a point just below the Gasport-Decew contact while the writer's sample came from about 5 feet lower down. This change in mineralogy illustrates the transitional nature of the Decew and is consistent with the depositional conditions.

The Decew at Brockport (4-5R) is mineralogically similar to that at Lockport except for less quartz and more clay, illitic instead of chloritic, according to the normative analysis.

The Decew at Clarendon (4-9R) has a considerably greater amount of quartz (20.6%) and more clay (18%) than the other Decew samples.

Physical Characteristics:

The outstanding characteristic of the Decew is its variable performance in soundness tests as is to be expected from a transitional rock. Sample DQ-1-1 tested by Mohammed did not fail soundness tests and had a low water absorption, while the samples tested by the writers (2a, 4a, and 5a) either had soundness failures or fairly high losses. All three of the samples failed the freeze-thaw test; 4a and 2a failed the magnesium sulfate test and 4a failed the sodium sulfate test. Water absorptions were high, 1.4 for 4a and over 1% for 2a and 5a. Porosities were less than that found by Mohammed but were in excess of 1.5%.

Gasport Member (6 samples)

The Gasport is the name given to a medium grained, grayish, crinoidal dolomite which occurs along the Niagara escarpment near Gasport, New York. The unit extends from Niagara Falls eastward to Brockport. It is 25 feet thick at Niagara Falls increasing to 30 feet at Lockport and thins to 25 feet at Royalton. The type-Gasport is the lithology seen at Royalton. However, at Lockport the stratigraphic position of the upper half of the Gasport is occupied by the variant lithologies (2c and 2c reef) and at Brockport the stratigraphic position of the Gasport is occupied by a dark colored, fine-grained, fossiliferous limestone with a high insoluble residue content (sample 5b). The 2c unit contains massive, structureless, dolomitized reef pods (2c reef) flanked by inter-reef zones of a silty, rather organic-rich, dark-gray,

fine-grained dolomite (2c). This unit is not found in any other NYS approved quarry, although at Royalton and Clarendon minor (several feet thick) 2c rock types were noted.

The following description of the Gasport is from the samples taken at Lockport, New York (5-5R).

1. Typical Gasport - Sample 2b

   Dolomite, medium-grained (0.5 to 1.5 mm), light gray. Abundant fossil fragments, consisting mostly of crinoid stems, were noted. Numerous small vugs occur.

2. C-unit variant - Sample 2c

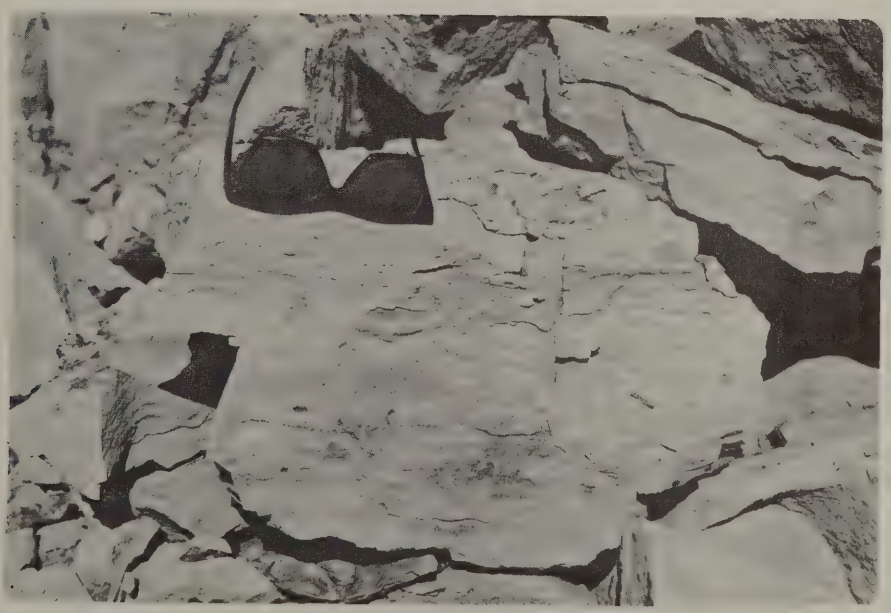
   Dolomite, fine-grained (0.1 to 0.5mm) medium dark gray; stratification in the form of slightly darker gray, wavy bands 1-2mm thick, sometomes enclosing lighter colored material. Some fossil debris.

3. C-reef variant - Sample 2c, reef

   Dolomite, fine-to-medium grained (0.1 - 2.0 mm) very light gray. A massive, structureless mound of dolomitized fossil debris with no recognizable fossil remains. Patches of light and darker gray material were noted along with argillaceous and carbonaceous material occurring along boundaries between patches. Several small stylolites.

4. Brockport lentil - Sample 5b

At Brockport (location 4-5R) a limestone unit occurs in the position which should be occupied by the Gasport. This unit contains many of the same fossils found in the Gasport just to the west at Clarendon, and is underlain by the Decew. This unit differs from the Gasport in that it has a relatively high insoluble residue content (about 25%), and is a limestone instead of a dolomite.



Photograph II-4. C-unit of Lockport formation, Lockport, showing deterioration due to weathering.

The rock is massive, dark-gray, fine-grained (0.5 to 0.1 mm) limestone with abundant fossils, especially brachiopods and crinoids, shaly partings about 1 to 2 mm thick and about 15% quartz.

Chemical and Mineralogic Characteristics:

The type-Gasport at Lockport (2b) is 94.7% carbonate which is 90% dolomite. According to the normative analysis there is 3% quartz and 9.8% clays which is apparently mostly an iron-sericite. The C-unit (2c) is 85% carbonate which is 92% dolomite and contains 3.3% quartz and 12% clay which is mostly chlorite with lesser amounts of sericite and iron sericite. A sample of this same unit studied by Mohammed has similar normative mineralogy. The Brockport unit (5b) is 73% carbonate which is 1/3 dolomite and 2/3 calcite, and contains 18% quartz and 7.5% clay mostly chlorite. The type-Gasport (sample 2b) is 94.7% carbonate which is 90% dolomite and 10% calcite, with the remainder clay, which is dominantly an iron sericite, and minor quartz. The sample of unit 2C (sample 2C) is 85% carbonate which is 92% dolomite. It contains 3.3 percent quartz and 12% clays which are a mixture of chlorite, sericite and iron sericite. The C-reef (sample 2c reef) is a relatively pure dolomite, 97% carbonate which is 89% dolomite. The Brockport lentil is a dolomitic, siliceous limestone, containing 73% carbonate (65% calcite, 35% dolomite) 18% quartz, 7.5% clay which is a mixture of chlorite, iron sericite and minor sericite.

Physical Characteristics:

The true specific gravities of all the Gasport samples, type-Gasport as well as Gasport variants, range from 2.54 to 2.85. Compressional wave velocities for the "typical Gasport" (2c, 3b, and 4b) are fairly consistent at about 1.90 X $10^4$ in/in/$^oF$. However the argillaceous and porous variants (2c-reef, C-1-1 and 2b) have low velocities.

Type-Gasport sample 2b has low losses on the soundness tests. On the Deval abrasion test the losses run over 4% with a failure for sample 3b (5.8% loss).

The Gasport variants, however, show a completely different pattern. The C-unit (sample 2C) failed badly with a 44.2% loss on the freeze-thaw test and 34.8% loss on the magnesium sulfate soundness test and was satisfactory on the sodium sulfate soundness test (3.9% loss) and the Deval abrasion test (4.6% loss). The Brockport limestone lentil (sample 5b) had a loss of 13.8% on the freeze-thaw and fairly low losses on the remaining soundness tests.

Goat Island Member (4 samples)

The Goat Island member conformably overlies the Gasport from Niagara Falls to Clarendon. It consists of brownish, brownish-gray and light gray, medium to thick bedded dolomite and is fairly non-fossiliferous except for several reef-zones near Lockport. The member is from 20 to 40 feet thick.

The Goat Island is represented in 2 quarries, 5-5R at Lockport and 4-9R at Clarendon where it forms the upper 22 and 5 feet respectively of each quarry. At Lockport two of the Goat Island units, 2d-lower and 2d-upper, occupy stratigraphic positions which place them in the Goat Island member although they are not characteristic of the unit. They are rather fossiliferous and evidently represent zones of persistent and abundant organic activity which left a fossiliferous zone not characteristic of the Lockport as a whole. The remaining two units, 2e at Quarry 5-5R and 4c at Quarry 4-9R are considered more typical of the Goat Island member. In the following discussion samples 2dl and 2du (the non-typical Goat Island) will be considered together and Goat Island (samples 2e and 4c) will be described.

2d-lower:

Dolomite, fine-grained (0.1 mm avg.), pale brown. Sample contains a large number of vugs ranging in size from 1 to 25 mm which are lined with calcite crystals 10 mm long and dolomite rhombs 1-2 mm long. Numerous cabbage-shaped patches of lighter colored material some 50 mm across evidently represent dolomitized stromatoporoid fossils.

2d-upper:

Dolomite, fine-grained (0.5 mm avg.), light gray. Massive. Some coarse grains (1.5 mm) replacing fossil debris. Many patches of light and dark gray material representing dolomitization of now unidentifiable fossil debris.

Chemical Characteristics, 2d-lower and 2d-upper:

2d-lower is, from normative analysis, about 96% carbonate which is 90% dolomite and 10% calcite. The rest is mostly clay (chlorite) (and no normative quartz). 2d-upper has only 88% carbonate which is again about 90% dolomite. This sample has 1.3% quartz and the rest clay, which is predominantly sericite, according to norm calculations.

Physical Characteristics, 2d-lower and 2d-upper:

The 2d samples have true specific gravities of 2.82-2.83 and are comparable in sonic velocities. Both samples have high water absorption and porosity. 2d-lower did not fail any soundness test although the magnesium sulfate loss was high (9.7%). 2d-upper had two failures: 10.6% on the abrasion test and 4.5% on the freeze-thaw. The losses were moderate on the sulfate soundness tests.

Typical Goat Island:

Typical Goat Island is found above the Gasport member from Niagara Falls to as far east as Clarendon and consists of 20 to 25 feet of brownish gray, fine-grained dolomite with a moderate insoluble residue content and only sparse fossils.

Chemical and Mineralogical Characteristics:

The typical Goat Island (2e) has a high dolomite content (90%). Normatively the rock is 92.4% carbonate which is 97% dolomite. The remainder of the sample is clays, illite with some sericite. Normative analysis indicates no quartz, but some was seen in thin section along with a trace of chert.

Physical Characteristics:

Samples of the Goat Island member have specific gravities, porosities and water absorptions which are typical of dolomitic rocks. Compressional wave velocities are from moderate ($1.8 \times 10^4$) to low ($1.46 \times 10^4$). The typical Goat Island (samples 2e and 4c) failed the 25-cycle freeze-thaw test with a loss of 3.8% and 7.0%. The sample 4c also failed the sodium sulfate soundness test with a loss of 6.1%.

Eramosa Member (1 sample)

In the Niagara Falls region the Goat Island is overlain by the Eramosa, which is a fine-grained, light gray weathering rock found between the Goat Island and the Oak Orchard members in the Lockport formation west of Lockport. The Eramosa is found in only the Niagara Stone Company quarry at Niagara Falls where it is 20 feet thick and occurs in the lower portion of the quarry but is not currently being quarried.

The Eramosa is: Dolomite, fine-grained to very-fine-grained (0.1 mm), dark gray to brownish gray. Some evidences of minute recrystallized crinoid stems. Slight mottling of olive gray patches suggesting stratification.

Chemical and Mineralogic Characteristics:

According to normative analysis the Eramosa is 80% carbonate which is 97% dolomite. The sample has no quartz but has about 20% clays which are dominantly illite with minor sericite.

Physical Characteristics:

Sample 1a has a true specific gravity of 2.82, a water absorption of 1.1% and a porosity of 0.4%. The specimen failed with a 30.3% loss on the freeze-thaw test and an 18.3% on the magnesium sulfate soundness test. The sodium sulfate and abrasion test losses were both 4.2%.

Penfield Member (4 samples)

Penfield is the name advanced by Zenger for the light brown to dark-brown, fine-grained dolomitic rocks of the Lockport formation which, in the Rochester-Penfield-Marion area, are subjacent to the Oak Orchard member. The Penfield member resembles the Oak Orchard member megascopically but differs markedly from it chemically in having a high silica content. The Penfield ranges from over 50% quartz sand (a dolomitic sandstone) at its base to 10-15% quartz at the top. It is commonly cross-bedded in the lower portions where it is most sandy.

The Penfield is not found west of Rochester or east of Marion. It is lenticular with a maximum thickness of 60 feet and pinches out both to the east and west. The contact with the overlaying Oak Orchard is gradational. Sample 7a is from the type locality in the Penfield quarry (4-4R).

Chemical and Mineralogic Characteristics:

Sample 7a has the 53.5% $SiO_2$ with a correspondingly low loss on ignition (14.3%) and low CaO and MgO content (16.7% combined). The normative analysis indicates a mineralogic composition of 52% quartz

and about 30% carbonate which is 86% dolomite and 14% calcite. The normative analysis also indicates 15% clay minerals which are mostly iron-sericite with lesser chlorite.

The Penfield sample from Marion (9) is quite similar in chemical characteristics, but the samples from Gates (6a and 6b) are stratigraphically higher in the Penfield member and contain lesser amounts of quartz.

Sample 6a has only 17% quartz and is 65.8% carbonate which is 95% dolomite. The remainder of 6a is clay which is mostly illite.

Physical Characteristics:

The four samples of Penfield have water absorptions of~0.9% with the porosity from 1.0 to 4.5%. The true specific gravities are lower than most other Lockport specimens because of the quartz content and they also have a lower average sonic velocity. The NYSDPW tests for all Penfield samples have only one failure, an abrasion test for sample 6b from quarry 4-6R (Gates) with a loss of 6.2%. Sample 6-a from the same quarry had a loss of 3.2% on the abrasion test. Other abrasion losses were 4.3% at Marion (sample 9) and 2.5% at Penfield (sample 7a). The freeze-thaw tests for all four Penfield samples were less than 1%. The magnesium sulfate soundness losses were variable, ranging from 3.1% for 6a (Gates) to 0.0 for 7a (Penfield) to less than 1.0% for the remaining two. The sodium sulfate soundness losses were comparable in all four cases.

Oak Orchard Member (6 samples)

Nearly 75% of the Lockport from Sodus to Niagara Falls is composed of one unit, the Oak Orchard. This unit is 125 to 150 feet thick and is found in four New York approved quarries (5-4R, 4-6R, 4-4R, and 3-5R). The Oak Orchard is a dark brown, fine grained dolomite characterized by a low clay content and low insoluble residue content, generally less than 14%. Locally this unit contains a considerable amount of bituminous matter which imparts on oily smell to the rock and an oily scum forms on the top of crushed samples which are dissolved in acid. In contrast to the extensive lateral variations displayed by the Gasport and Goat Island, the Oak Orchard is characterized by only slight variations, vertically or laterally.

Two Oak Orchard samples are described, sample 1b from the Niagara Stone Company quarry at Niagara Falls (5-4R) and sample 7b from the Dolomite Products Co. quarry at Penfield (4-4R).

Specimen 1b. Dolomite, fine-grained (0.25 to 0.75 mm), dark gray to chocolate-brown in color. Mottled lighter and darker brown. Argillaceous layers 0.5 mm thick. Scattered vugs containing massive gypsum, quartz, dolomite and sphalerite noted.

Specimen 7b. Dolomite, fine-grained (0.25 to 0.75 mm), light-brownish gray. Mottled lighter and darker material. Some vugs containing gypsum, calcite and dolomite noted.

Chemical and Mineralogic Characteristics:

Normative analysis indicates that sample 1b consists of 97.6% carbonate, which is 94% dolomite, and the rest clay which is mostly chlorite.

Sample 7b is 90% carbonate which is 94% dolomite. The sample has 3.4% quartz and 9.5% clay which is chlorite, sericite and iron sericite. The essential difference between 1b and 7b is the greater amount of clastic material in 7b. This, however, is apparently a local variation, because at Sodus the Oak Orchard samples (8a, 8b, 8c) are again over 97% carbonate.

Physical Characteristics:

The true specific gravities of the Oak Orchard range from about 2.83 to 2.88 with water absorptions of 0.7% (1b) to 1.8% (7b). Porosities are about 1.35% for both samples. Sonic velocities are fairly high, $1.9 \times 10^4$ for 1b and $2.1 \times 10^4$ for 7b (both normal to bedding). All the Oak Orchard samples had fairly high Deval abrasion losses with sample 8a a failure with a 6.9% loss. No sample of Oak Orchard had soundness failures.

## PAMELIA LIMESTONE AND DOLOMITE FORMATIONS (7 SAMPLES)

The Pamelia formation belongs to the Black River Group which constitutes the Mohawkian Series of the Middle Ordovician. The Black River beds are chiefly confined to the Mohawk, Black River and Champlain Valleys and are most prominently developed in the Watertown-Lowville area. In Kingston Township of Ontario there are many small quarries which cut portions of the Pamelia.

The Pamelia varies much and rapidly in thickness, because it lies upon the irregular surface of various pre-Cambrian crystallines and Cambrian sediments. It is divided into two parts, with the upper division generally more persistent than the lower.

At quarry #7-6R in Lowville, this upper division rests uncomformably on pre-Cambrian granite (quartz syenite) and consists of medium light gray or greenish gray, sandy, interbedded dolomite with medium gray, somewhat magnesian and sublithographic limestones. The dolomite and dolomitic limestones weather to a buff, yellow-brown or greenish hue. Stylolites and nodules of crystalline calcite in the sublithographic section are common. Well-preserved ripple marks and mud cracks are found at several horizons throughout the formation.

The most striking characteristic of the Pamelia is the layer by layer alternation of sublithographic argillaceous limestone which is typical of the Lowville formation and buff-weathering argillaceous, dolomitic limestones which are typical of the lower Pamelia.

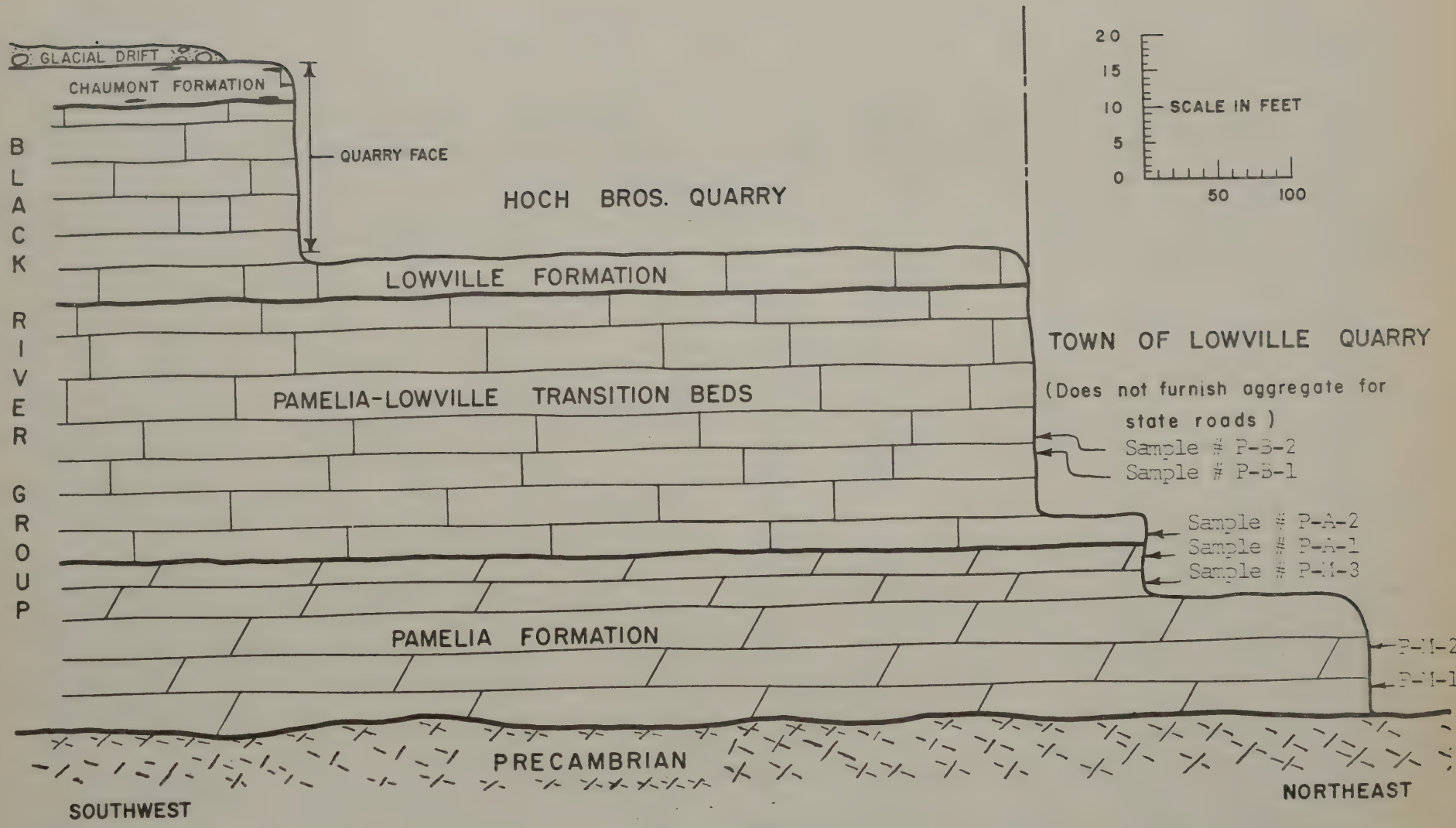



Figure II-2

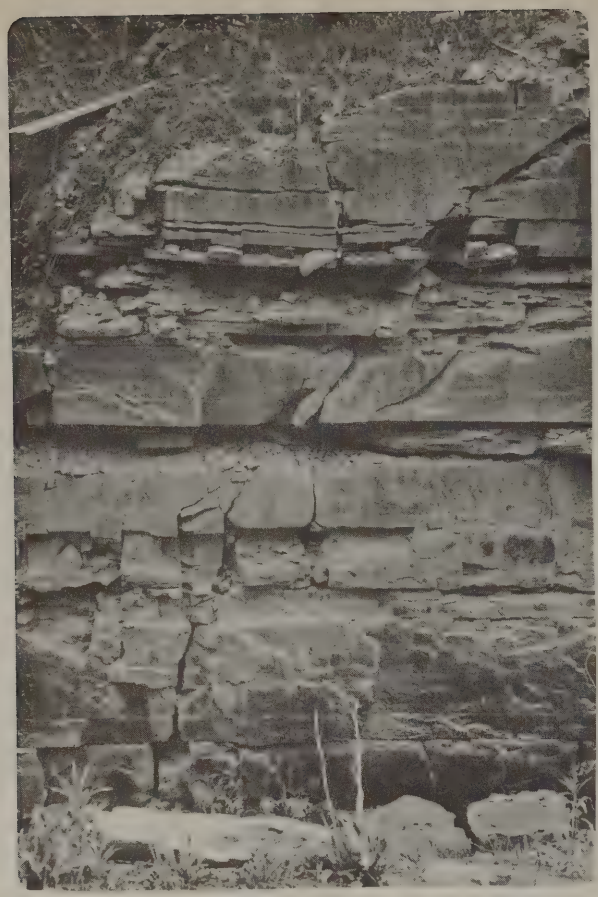
QUARRY NO. 7-6R

After N. Y. S. D. P. W. Research RR 61-3

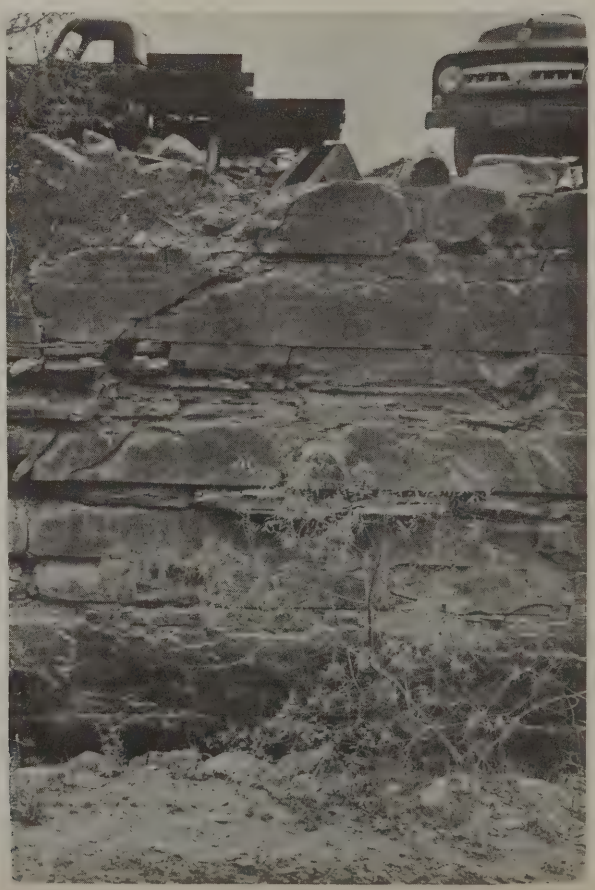
Chemical and Mineralogic Characteristics:

The Pamelia formation varies radically from layer to layer in its chemical characteristics as might be anticipated from field observation of the variable color of the weathered surfaces. No sample of "average Pamelia" exists in the upper Pamelia or the Pamelia-Lowville transition beds. The total carbonate varies between 55% and 95% with the dolomite up to 45% of the total. The clay content varies from 2% to 22% and free silica from 0% to 24%. No simple relationship could be seen between calcite-dolomite content, silica content and clay content. Sample P-B-2 has a deleteriously high expansion in the dedolomitization test.*

*Dedolomitization not considered proven. However rock is of very questionable quality for other reasons.



Photograph II-5. Pamelia formation, Lowville, showing intensely weathered argillaceous dolomitic layers alternating with relatively fresh limestone layers.



Photograph II-6. Pamelia formation, Lowville, same face as above but showing the weathered dolomitic layers grading into less obviously weathered material. Bush is five feet tall.

Physical Characteristics:

Specific gravity and thermal expansion values vary as would be anticipated from the mineralogies, i.e. calcitic layers have the lower specific gravities (2.71 for calcitic layers versus 2.78 for the most dolomitic measured) and lower thermal expansion (about 4.00 X $10^{-6}$ for a calcitic layer versus about 7.42 X $10^{-6}$ for a dolomitic layer). Compressional wave velocities range from 1.70 X $10^{4}$ to 2.08 X $10^{4}$ with the average of the dolomitic layers less than the calcitic but the second highest sonic velocity (2.04 X $10^{4}$) is from a dolomitic layer. Water absorptions are low for the calcareous layers and moderate (0.5 to 0.9% for the dolomitic layers) and three of the dolomitic layers failed badly in several soundness tests. Specimen P-B-2 decomposed badly on a wet-dry test. Basically, the dolomitic layers are likely to be unsound, "alkali-reactive", and weather badly on exposure (see photo on previous pages).

## CATSKILL GRAYWACKES

The term "Catskill graywackes" refers to the graywacke portions of several formations which occur in the Catskill region from Binghamton in the west almost to the Hudson River to the east. The formations are the Stoney Clove and Lower Katsberg of the Sonyea group and the upper Katsberg and Slide Mountain formations of the Java and West Falls groups, all of Upper Devonian age. The graywacke layers which are quarried occur between shale and siltstone layers which are generally shades of green or red. Medium to dark gray shale occurs in the graywackes in sinuous bodies with a lenticular cross section. The graywackes may also contain gray shale as clots or pebbles.

The graywackes tested in this research were mostly medium gray, greenish gray to very light gray, medium grained, argillaceous sandstones. Detailed logs of quarry faces were not made because of the extreme heterogeneity of the rock types and detailed descriptions of each rock tested are not included in this report. (For detail of locations, etc. see Miller and Senechal, 1962).

Chemical and Mineralogic Characteristics:

The five Catskill graywackes which were analyzed had a remarkable chemical similarity. The silica content was between 74% and 77.4%; $Al_2O_3$, 9.90% to 12.32%; total iron oxides, 4.02% to 6.15%; total MgO and CaO 2.30% to 3.72%; total alkali, 0.65% to 2.99% with $K_2O$ predominant.

Modal analyses by Miller and Senechal (1962) of four samples had the following approximate average mineralogies: 65% free silica (quartz and quartzite) 1.8% feldspar, 19.7% muscovite, 3.1% chlorite, 5.1% clay sized particles and 1.3% carbonate.

Normative analysis of average graywacke indicates about 50% clay minerals (montmorillonite and illite). It is probable that more clay is present than indicated by Miller and Senechal, but a high montmorillonite content is very unlikely.

X-ray analysis indicated the absence of expanding clays, not a surprising situation considering the great stability of the graywackes under weathering conditions. Recementation by carbonate and silica near cliff fronts was observed by Miller and Senechal (p. 7).

Physical Characteristics:

The percent porosity ranged from 0.0% to 3.0% for fifteen samples tested with the Ruska permeameter with water absorptions on 12 samples varied from 0.50% to 1.96% by weight for 150 hours of soaking. Eight of the 18 samples tested failed N.Y.S.D.P.W. magnesium sulfate soundness test for class B coarse aggregate and 15 of 18 samples failed the freeze-thaw test. However, no samples had the extremely high losses on freeze-thaw test which were found for some of the argillaceous dolomites.

## SUMMARY AND CONCLUSIONS, PART II

The causes of some major variations of chemical, physical and petrographic variations in sedimentary rocks of the types considered in this project are:

1. Physical environment of sedimentary deposition such as:
   a. depth of water, which determines whether reefs may form in carbonate rocks and the likelihood of silt and clay being deposited. (The former is favored by shallow water, the latter by deep water).
   b. velocity of water currents which influences grain size deposited.

2. Chemical environment of sedimentary deposition and compaction, such as the conditions which cause limestones to alter to dolomites, cause chert to replace carbonate rock on the sea floor and favor the growth of shell fish and reefs.

3. Late post-lithification events such as the nature of weathering relative to the rock types, faulting and metasomatic alteration of rocks.

The major units tested have the following general characteristics:

The Nedrow member of the Onondaga formation is a medium dark to dark gray, argillaceous, dolomitic limestone which is notably chert free. Sonic velocities, water absorptions and soundness losses are all

moderate and although the rock is not of very high quality, it seems to be basically satisfactory for aggregate.

The Manlius formation is primarily a medium to dark gray limestone which has a high carbonate content, generally about 90%, which is mostly calcite. Certain minor layers such as the light-gray layer of the Thacher at Dewitt and parts of the Elmwood are dolomitic. The major impurities are clays and free silica, primarily silt. The average Manlius is characterized by high sonic velocities, in excess of $2.00 \times 10^4$ ft/sec., low water absorption, porosity and thermal expansion (about 3 to 4 $\times 10^{-6}$ / $1^{\circ}$F). The average Manlius is a sound rock as indicated by low losses on soundness tests and by its service record. The only layers of questionable quality, as indicated by soundness tests, are the dolomitic layers.

The Cobleskill formation is a medium gray, calcareous dolomite which is from 83% to 93% carbonate (about 55% dolomite in the average specimen). The major impurity is clay, with silty quartz a minor constituent. The samples tested had suprisingly high compressional wave velocities (about $2.00 \times 10^4$ ft/sec. average) and intermediate thermal expansions. The soundness tests are considered satisfactory, although all samples were marginal in the freeze-thaw test. Water absorptions were low or moderate.

The Lockport formation is a medium to light gray, commonly tannish, dolomite which is characterized by a moderately high carbonate content, usually 80% to 98% which is primarily dolomite. The average percent of noncarbonate impurities is notably higher than the Manlius, but both the purest and least pure carbonate rock tested in this project were in Lockport samples (from about 2.5% to nearly 70% impurities). Physically the Lockport formation is characterized by low compressional wave velocities, around $1.8 \times 10^{4}$ ft/sec., and high thermal expansion, up to $9 \times 10^{-6}$/in/in/1°F. The Lockport rocks generally have relatively high water absorptions, over 1%, high porosities and high soundness losses, particularly in freeze-thaw test, are common. The "C-unit" is decomposed by wetting and drying.

The Pamelia formation varies between strongly contrasting lithologies, a light gray limestone to a greenish gray dolomitic limestone. The individual layers also vary considerably in the non-carbonate impurities, clays and free silica. The Pamelia is fairly high in quartz with a high quartz-clay ratio. Basically the calcite-rich layers are sound and have high sonic velocities, low soundness losses and low absorptions whereas the dolomitic layers have low sonic velocities, high soundness losses and high water absorptions. Some dolomitic Pamelia fails on wetting and drying.

The Catskill graywackes are characterized chemically by a high non-expansive clay content and a high silica content. The specimens

tested have high porosities and permeabilities and are generally not satisfactory on freeze-thaw and magnesium sulfate soundness tests. Their service record, to date, is apparently excellent and therefore the stone is presumed to be of good quality for use in concrete.

# PART III

## THEORETICAL CONSIDERATION OF FREEZE-THAW SOUNDNESS OF AGGREGATE

## INTRODUCTORY STATEMENT

Because of limitations of time and money it has not been possible to pursue many of the ideas in Part III. However, important phases of research are the hypothesis and the speculative idea, because they are basic to experimentation. Part III of this paper is a theoretical evaluation of various tests and data. The purposes are to ask questions, to suggest some alternative explanations to various phenomena, to indicate areas where further research may prove productive, and to suggest a simplified system of aggregate testing which may provide more definitive answers about soundness of aggregate in concrete.

Some aspects of freezing and thawing are discussed first for rocks in nature and then for concrete. Some details of various freezing and thawing tests are discussed and related to possible freeze-thaw situations in exposed concrete.

## FREEZING AND THAWING OF ROCKS IN NATURE- RELATIVE SOUNDNESS IN CONCRETE

A quick approximation of the ability of a rock to withstand freezing and thawing in concrete can be gained by observing outcroppings in the field or the effect of weathering on rocks in old rock cuts. A basic rule would seem to be: If a rock satisfactorily withstands natural freezing and thawing, it will be sound in air-entrained concrete; but if a rock breaks down in natural exposures, it may or may not deteriorate in air-entrained concrete. In all proven or probable cases of distress in concrete due to coarse aggregate, the offending aggregate layer has been observed to deteriorate in nature.

Rocks with questionable service records in New York are: dolomitic Thacher member of the Manlius from the Syracuse area, Cobleskill and Rondout formations from the Auburn area, white chert (#45 chert of Dunn and Ozol, 1962) from the Stafford area and the Decew formation from the Rochester and Clarendon areas. (The latter two aggregates were used in non-air-entrained concrete, but failure in air-entrained concrete is not proven). In addition, shales and argillaceous siltstones are causes of popouts in concrete in several areas where they have been inadvertently included in the aggregate. All of the above rocks fail to outcrop naturally, and decompose rapidly on a quarry floor or in rock cuts. Freeze-thaw tests detect these questionable rocks and, except for the #45 chert, losses tend to run very high, up to 80%.

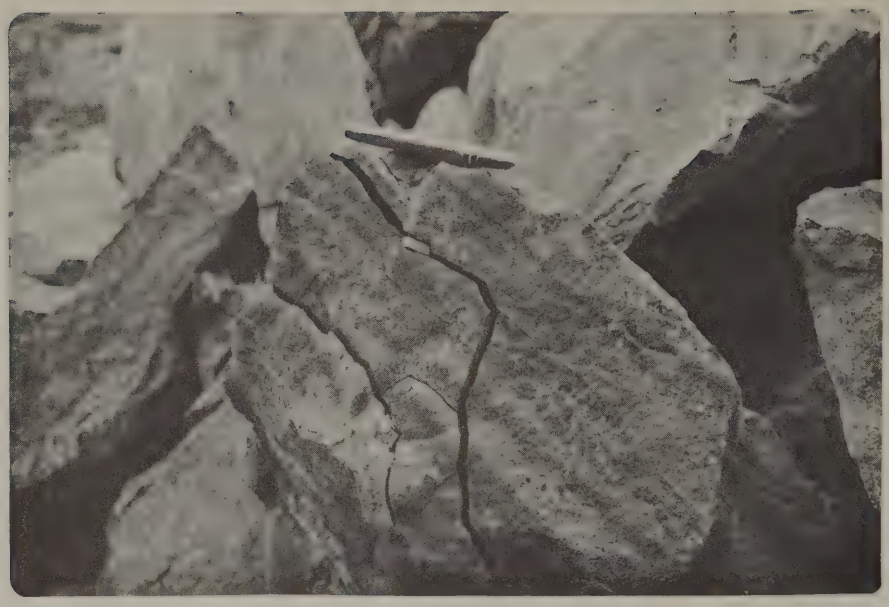
The number #45 chert, with a loss of 3.65%, is inconsistent but still a failure according to current N.Y.S.D.P.W. standards. It has very high losses in the sulfate soundness tests. The #45 chert has a loss of 33.84% on the sodium sulfate soundness test and a loss of 17.17% on the magnesium sulfate soundness test and is the only rock tested with relative soundness losses in this order, i.e. the lowest loss in the freeze-thaw test and the highest in the sodium sulfate.

Photographs III-I and III-2 show some of these rocks as they appear in some quarries in New York. Note the typical deterioration by conchoidal fracturing.

Other rocks decompose on weathering, fail the freeze-thaw test, and yet have no proven use failures; as examples, the C-layer of Lockport dolomite and the dolomitic Pamelia at Lowville.

In addition, some rocks outcrop prominently in cliffs (have no apparent natural freeze-thaw sensitivity), have never failed in use, and yet have high losses in both the freeze-thaw and magnesium sulfate soundness tests. The Catskill graywackes, and much of the Little Falls dolomite, the Lockport dolomite, and various dolomitic layers of the Manlius formation are typical examples.

Summarizing: All rocks which have been observed to deteriorate rapidly on exposure, also fail the freeze-thaw test. Among these rocks are all known use-failures in New York State. However, failure in nature and in the freeze-thaw test as run by the N.Y.S.D.P.W. is not an



Photograph III-1. Decew member of the Lockport formation. Boulder on floor of quarry at Lockport. Typical deterioration due to weathering.

Photograph III-2. Elmwood member of the Manlius formation, Auburn. Located about 40 feet above quarry floor. Note deterioration caused by weathering.

assurance of failure in concrete.

## CRITICAL SATURATION AND DIRECTIONAL FREEZING

Critical saturation (over 91.7% water filled pore space) in a rock is ordinarily a requisite for freeze-thaw failure; however many rocks are porous in nature, critically saturate, and do not disintegrate on freezing and thawing. Outcrops of sandstones, siltstones and carbonate rocks along and in the beds of small streams and on the shores of lakes and swamps in New York must be saturated locally with water and yet they do not deteriorate by freezing and thawing. Similarly vast areas of low-lying swamps and lakes in eastern Canada have water-saturated outcrops at the water level which must freeze to considerable depths during the winter, and undergo many cycles of freezing and thawing each season.

The reason many rocks which must be critically saturated do not fail in nature is probably the partial result of the phenomenon of directional freezing, i.e. freezing from an exposed surface inward with the inward migrating "ice front" driving water ahead of it to take up the 9% expansion in the transition of water to ice.

Figure III-1 is a sketch showing the conditions in an open, porous system, the rock saturated and permeable enough so the water can escape ahead of the ice. (The lettering refers to the formulation on the next page.)

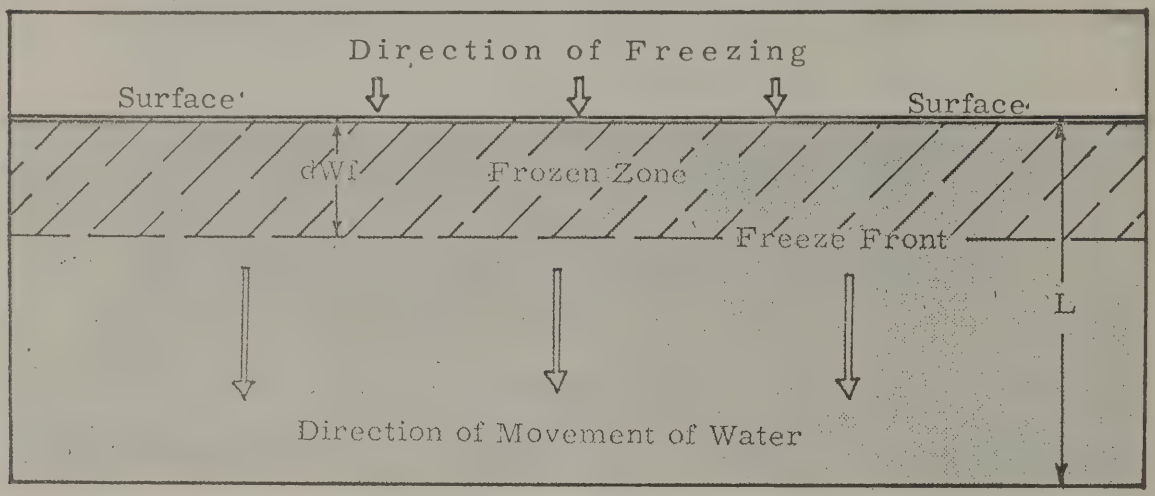



Figure III-1

Ice at 32°F has maximum volume and minimum strength. It molds into the interstices of a rock by growth and by gliding on the (0001) plane*. The expansion is taken up by pushing water ahead of the freezing front or the zone of freezing. (Freezing of water begins at 32° F, but in a system of this type with strong surface attractions final freezing of all water is at much lower temperatures.)

*Plane perpendicular to the major crystallographic axis of ice.

Yet, as previously noted, many rocks with porosities and permeabilities which are comparable to those assumed by Verbeck and Landgren outcrop prominently in various areas of New York State. Saturation must occur locally, as in stream beds, along lake shores, and at zones of contrasting permeabilities in cliff exposures. The dimension L for outcrops must be very large and hence the potential pressure ($P_{max}$) due to an advancing ice front could be very large also. Intuitively a geologist might question the Verbeck and Landgren formulation, because if it were true, deeply saturated outcrops should not occur at all.

The major factor which causes build-up of pressure ahead of an advancing ice front is the opposing force which prevents movement of 9% of water out of the system when water freezes. The opposing force in a simple, porous medium would seem to be the force which pulled the water in. Where the porosity is not complicated by other factors, capillary forces would seem to be the major force which retains water. Probably in any particular specific situation this force which acts against the loss of 9% of the water would be the minimum capillary force in the system. Stated differently, the water which leaves the system ahead of an advancing ice front would take the path of least resistance.

A static measurement of capillary force is the height to which water can move in a tube against the force of gravity. This static force is generally not very large, i.e. unlikely to be greater than the tensile strength of most rock. It is difficult to get exact figures for the maximum potential rise of water into natural porous media but the capillary rise, according to Todd (1959, p. 22), might be as

much as "several feet in clay". (However, as will be indicated later, clay may take water into its structure and is hygroscopic and therefore cannot be considered a simple capillary system.)

The question of how much force is required to push 9% of the water held by capillary forces out of a system is difficult to evaluate. At one extreme would be a high impact force, a water hammer, in which the potentially disruptive forces transmitted into the aggregate could be very large, up to the impact force itself. At the other extreme would be a slowly applied force tending to push capillary-held water out of a rock. A force which is equal and opposite to that of capillary pressure should be one which moves water out of the system at the same rate capillary pressures moved it in. A force which is applied at such a rate as to push water out at a slower rate than entered should not be capable of creating internal pressures which are greater than the capillary forces themselves. A major question then would seem to be: How do the rates of entry of capillary water compare with the rate of egress of the 9% of water forced ahead of a moving freezing front?

The time required to absorb a large percentage of the water in a typical aggregate by capillary action is a matter of minutes or a few hours (see Figure 1-6) and likely to be far less than the time to freeze a rock mass. Such water is that which moves in easily. (To critically saturate a particle may require much more time). The 9% of water which moves ahead of a freeze-front, however, is certainly that water which moves most readily or is least tightly held.) It might be reasoned from this that the force built up in driving out the least

tightly held 9% of water in a particle ahead of an advancing ice front should be no greater than the minimum capillary pressure which opposes it.

The concept that particle size of aggregate is critical in the soundness of concrete would seem to be questionable and much more work should be done before the concept is widely applied.

## HEAT LOSS AND FREEZE-THAW SOUNDNESS

### Heat Loss and Rate of Freezing of Water

In Verbeck and Landgren's equation for estimating the maximum hydraulic pressures which may be built up within aggregates,

$$p_{max} = \frac{0.09\ (dW_f/dt)\ L}{27.7K}$$

the rate of freezing $dW_f/dt$ is a function of: the specific heat and thermal conductivity, specific heat, the latent heat of transition of water to ice, the total water in the system, the thermal gradient within the system and the thickness of the insulating layer above the freezing point.

The rate of movement of the ice front must vary from a maximum at the surface where heat is lost to zero at the maximum depth of frost penetration. The maximum disruptive force for saturated material in a single cycle of freezing occurs during the freezing of the first incremental layer, because that is the peroid of maximum rate of freezing or heat loss.

With no absorbed water, assuming a specific heat of 0.20 cgs units, a gram of rock will cool $1^{o}$ for each 0.2 calories lost. But with 1% of water by weight the number of calories required to cool a gram of rock plus the water from $+0^{o}C$ to $-1^{o}C$, is 1.03 calories, i.e. an increase by a factor of 5.1. At 10% water by weight the increase is to 8.41 calories for the same temperature range or nearly a factor of 42. Other things being equal the rate of movement of the ice front decreases by a factor of 42 as the water content increases from 0.0% to 10%. Figure III-2 shows this relationship.

The above discussion is based on the assumption that all of the water is freezable. Actually some component of the water in an aggregate will not freeze under normal conditions, the percentage being very high with exceedingly small pores. Considering this factor the actual average curve lies somewhere below the straight line. There is no fixed position for such a correction curve, because the amount of nonfreezable water is related to both pore size and pore volume. The position plotted on Figure III-2 is from the typical quantities of nonfreezable water given for various percent porosities by Verbeck and Landgren (1960).

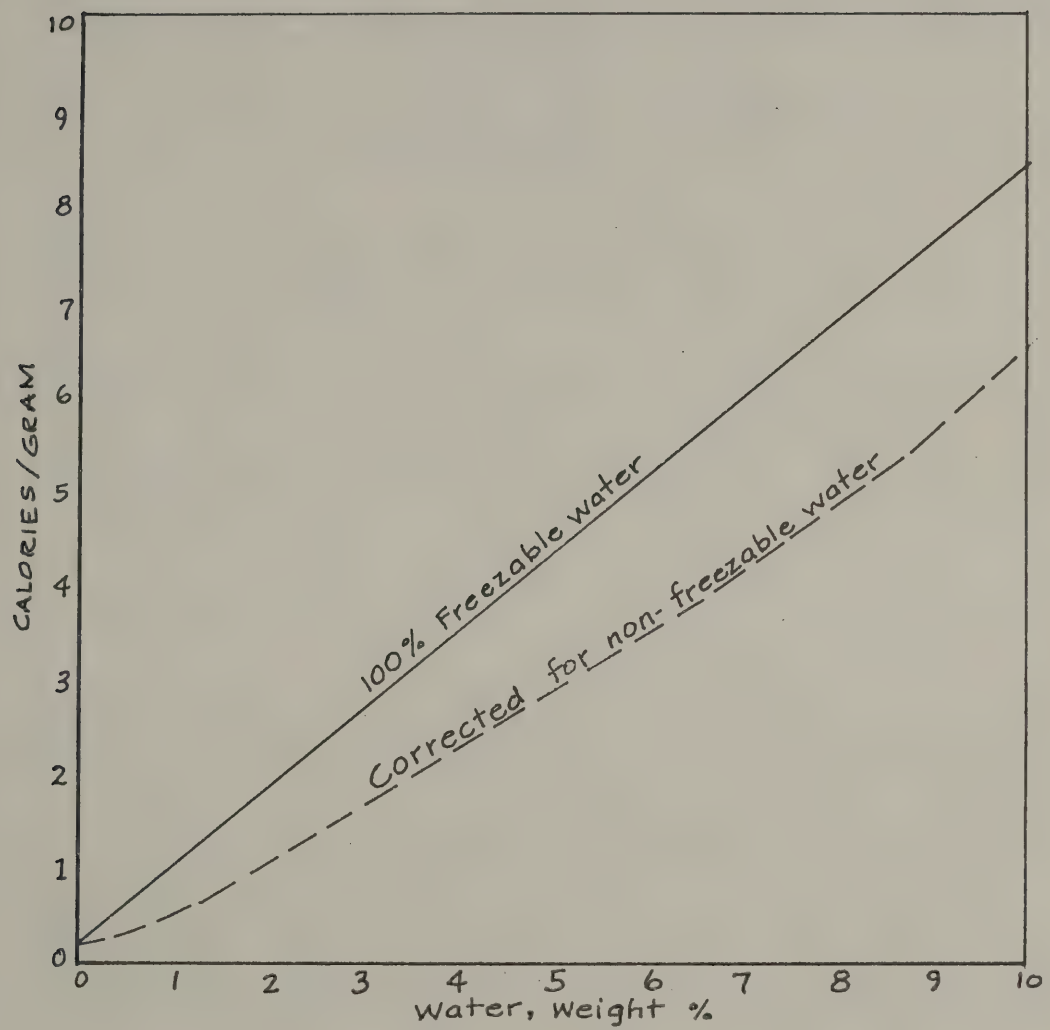



Figure III-2

RELATIONSHIP OF HEAT LOSS TO WATER CONTENT OF SATURATED AGGREGATE OF UNIT WEIGHT; T RANGE 0°C TO -1°C

Heat Loss and Rate of Expulsion of Water

Figure III-3 relates the quantity of water expelled from saturated aggregates at various water contents as a result of an advancing ice front assuming a heat loss of 1.03 calories in the range 0°C to -1°C. The heat of 1.03 calories is approximately that required to freeze completely the water in one gram of aggregate containing 1% water. One gram of aggregate with 1% water could expel .009 grams of water ahead of the freeze-front. However, aggregates with 5%, 10% or 50% water would expel only .0011 grams of water for the same heat loss.

The significance of this is that given a constant rate of heat loss, the amount of water expelled per unit of heat from aggregates containing more than 1% water is not notably increased with increasing water content. The rate of expulsion is far more influenced by heat conductivities of the components of the concrete system which may vary over a considerable range. (Figure III-3 is valid only for an incremental movement of the ice front. The thermal barrier of a rapidly moving ice front retards the rate of movement. But this effect is offset to some extent by the low heat conductivity of ice in water-rich rocks.)

The dashed line shows the position that the curve might assume if the non-freezable water is considered. In rocks with low absorptions of water in very small pores, almost none of the water is freezable at 0°C, because of surface effects. The rate of expulsion of water for water absorptions below 1% drops off so rapidly that the likelihood of

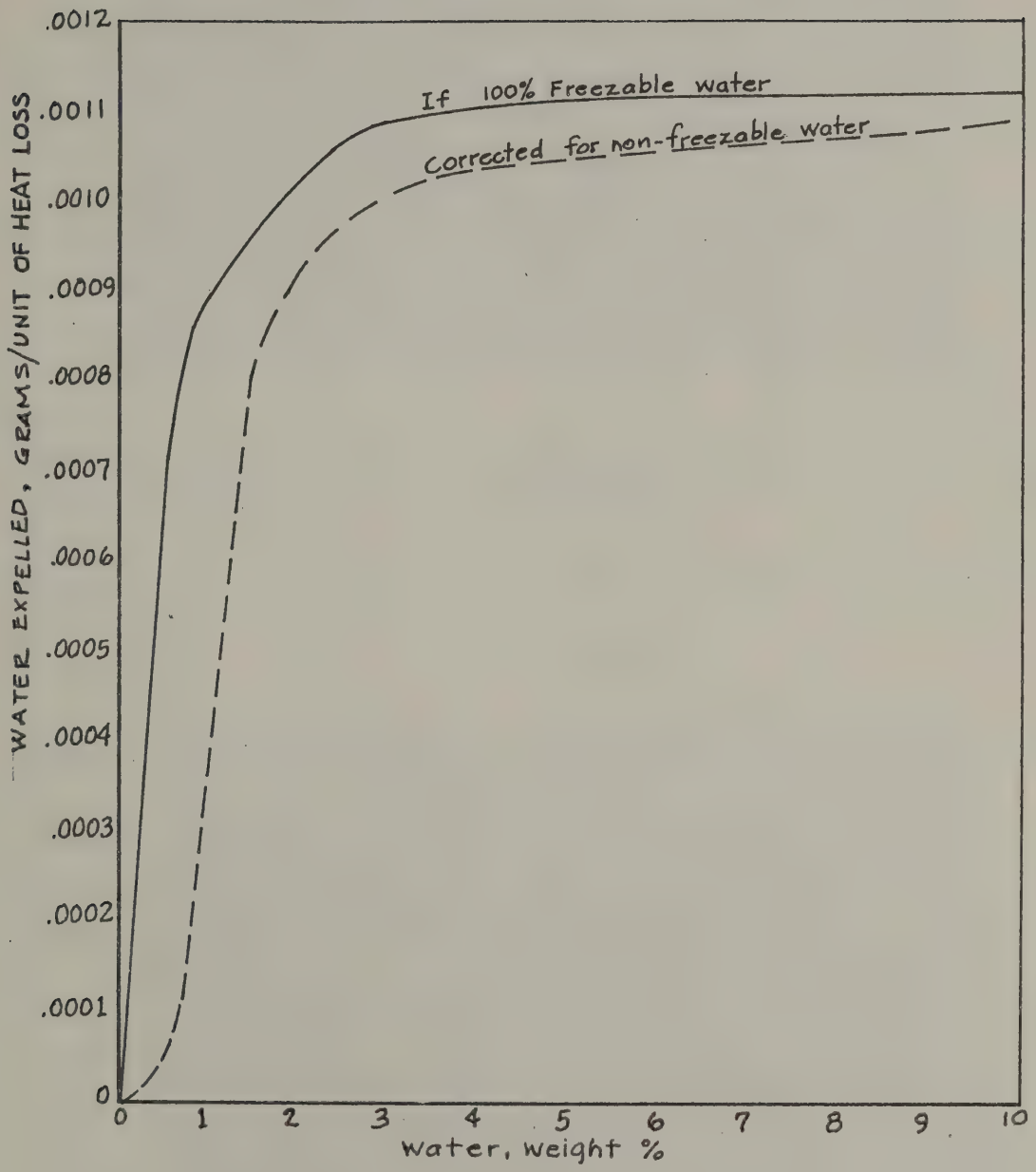



Figure III-3

WATER EXPELLED FROM AGGREGATE PARTICLES OF VARYING WATER CONTENTS, ASSUMING HEATLOSS OF 1.03 CAL. T RANGE 0°C TO -1°C.

freeze-thaw failure due to hydrostatic pressure on the aggregate-cement interface seems to be remote.

For aggregates with water absorption of about 1% the rate of water loss ahead of a freezing front does not change appreciably, assuming constant thermal conductivities. Therefore the total movable water is not a major factor in disruption of the aggregate. The major consideration apparently is the ability of the portland cement paste to absorb the expelled water at the rate typical for freezing saturated aggregates with more than 1% absorption.

A generalized mathematical expression for this relationship would include:

$$P = f\left( \frac{V_v}{V_p} \quad X \quad \frac{1}{Kt} \right)$$

Where:

$P$ = the pressure developed at the aggregate-cement interface,

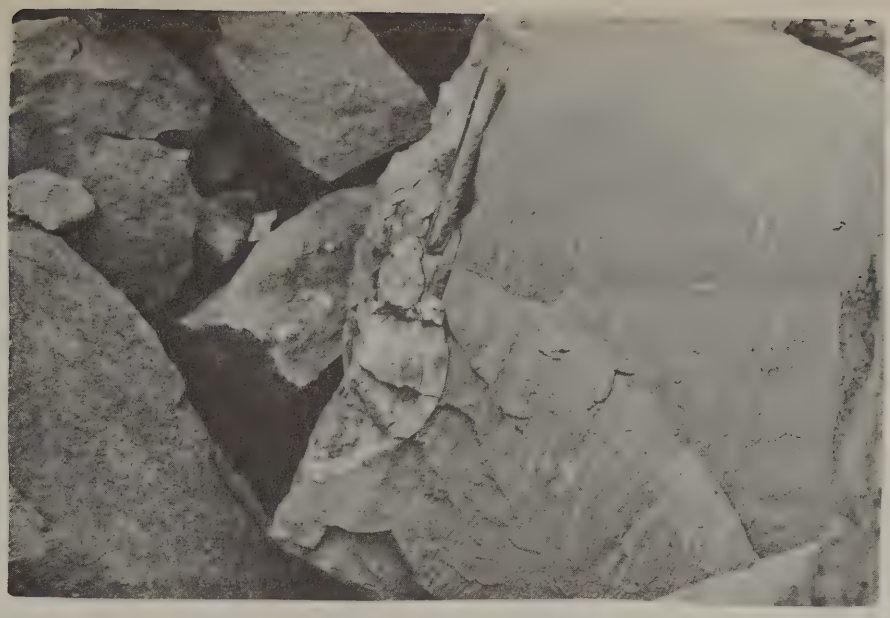
$V_v$ = the volume of expelled water, / unit surface area of aggregate

$V_p$ = the volume of pore space in the cement paste,

$K$ = the permeability of the cement paste,

$t$ = the time during which $V_v$ is expelled.

A theoretical study of the above expression through dimensional analysis followed by a series of laboratory experiments based on the study would seem to be a very important line of research.



Photograph III-3. Number 45 chert, Stafford. The chert typically fractures conchoidally on weathering.

Photograph III-4. Number 45 chert, Stafford. Weathered as above.

The water content has two further moderating influences on the rate of heat loss and the function $V_v/t$ which are here mentioned for sake of completion but will not be analyized further in the present report. (1)The thermal conductivity of ice is a little over 2 mcal/cm/sec/°C whereas most rocks have conductivities of over 2 times this figure. In addition, the thermal conductivity of water is only 1.2 mcal/sec/°C. Therefore as the water content increases, the freeze-front would probably advance more slowly because of a lower rate of the increase of resistence to heat flow. (2) Very probably the heat required to freeze tightly held capillary water is far in excess of the 82 cal/g assumed in the above discussion.

## CRITICAL SATURATION AND EXPANSIVE REACTIONS

An important consideration is the degree of saturation of aggregate. If the quantity of water in a fragment of aggregate exceeds 91.7% of its full saturation (the critical saturation), the particle might be unable to take up the expansion occuring during the water-ice transition. If critical saturation is reached, the likelihood of disruption of the particles is, therefore, greater. In addition, the expulsion of water into voids of the cement paste around an aggregate particle may create great pressures if the cement cannot absorb the water at the rate of expulsion or in the volume expelled.

In field conditions it is doubtful that most porous aggregates can become critically saturated in air entrained concrete, because there is simply not enough time to transmit enough water (liquid or vapor) to a particle of aggregate through the relatively impermeable cement membrane (for instance see Verbeck and Landgren, 1960, Tables I-IV). However, water-hungry rocks, such as #45 chert, the C-unit of the Lockport and the dolomitic Thacher, may well critically saturate during the mixing of the concrete. Whether or not they are capable of causing distress in concrete is likely to be a function of curing time, weather conditions, and local drainage conditions. Once wet these rocks require more time to dry out than other aggregates. But once they have dried somewhat, they may never cause distress. The fact that the service records of the water-hungry and water retentive rocks are not always bad (in fact are usually good) may be the result of local curing and moisture conditions as suggested above.

Freeze-thaw sensitive aggregates have a group of similar qualities. This group can be reduced to two apparently essential characteristics: (1) rapid water absorption to critical saturation and (2) expansive reactions. It seems likely that the correlation of the two characteristics and bad service record is not fortuitous. A partial and hypothetical explanation follows:

The No. 45 type of white chert of Dunn and Ozol (1962) causes pop-outs in western New York (Paul Bird, oral communication). Failure of this chert was a major reason for the alkali reaction studies.

No. 45 chert is very chemically reactive according to the quick chemical test, but it did not cause excessive mortar bar expansion in any of the 12 fabricated bars with varying ratios of chert, as was the case with other cherts tested. The interpretation of lack of mortar bar expansion is that the reactant products filled the pore space (water absorption 3.89%, nearly four times as high as the most absorptive of the other cherts tested in mortar bars). Filling of pore spaces with reactants has two probable effects: (1) it blocks the expulsion of water. (2) By expansion it tends to fill pores and facilitate critical saturation. Strong contributing factors are: (1) the tendency of this chert to hold water tightly, once saturated (see Part I) and (2) rapidity with which alkali-reactions may take place (Feldman and Sereda, 1961, p. 211).

Dedolomitization could create the same situation and for very similar reasons. In this case the pore spaces would be blocked by brucite and calcite. Feldman and Sereda (1961) suggest a substance of unknown identity causes the major expansion during dedolomitization. The effect, however, is the same, i.e. blocked pores.

Dolomitic carbonate rocks with disseminated clays, particularly where the clays are along grain boundaries, could develop a similar problem, but in this case expanding clays would be the expansive substances which retard the movement of water. (From the author's experience there is a tendency for some dolomites to reject clays during crystal growth so that the clays are concentrated along dolomite grain boundaries. C-1-1, the most expansive in the wetting and drying test, is a good example of this texture. Recrystallization of calcite also may result in the rejection of extraneous material as evidenced by clay along stylolites. Most non-shaly carbonate rocks, however, usually have the clay completely enclosed in the crystals or discontinuously disseminated among microcrystalline calcite. Almost all of the limestones and most of the dolomites studied on the present project have this sort of texture.)

A way of viewing the above phenomena is that in each case the solution enters a rock with a given porosity and permeability, saturates the rock and then is entrapped because of a radical change in pore characteristics. (Rocks with high water absorption and low porosities probably are adsorbing water into clays). An aggregate with such entrapped water may then be abnormally freeze-thaw sensitive and the concrete can become distressed. Distress due to such entrapped water could occur long before other forms of distress could be effective. The temperature at which adsorbed and inter-lattice water in clay freezes is not known to the author. However, the freezing of clays is readily

observed and certainly occurs within winter temperature ranges normal to the northern United States.

It is interesting to note that the chemical reactions or the expansion of clays alone may be enough to cause deterioration of concrete. Presumably the reactions can become deleterious in themselves if the expansion cannot be taken up by either the aggregate particles or the portland cement paste. For instance, non-porous, alkali reactive chert could cause enough distress to disrupt concrete.

## THE DETECTION OF EXPANSIVE REACTIONS

For the chemical reactions, radical changes in pH of a sodium hydroxide solution in contact with the aggregate could be the quickest indication of potential reactivity.

For clay-rich rocks which do not actually expand during water absorption the problem would not be so simple, because changes in the character of the water would probably not be significant, Rate of water absorption and water loss can be used to detect such water-hungry rocks (see Part I) when the rock is fresh (as from a core). Weathered surfaces are excellent indicators of the freeze-thaw sensitivity of such rocks.

Photographs I-1,2,3,4, and 5 show the sensitivity of some water-hungry dolomites to freezing and thawing (or wetting and drying). Photographs of #45 chert, which deteriorates on freezing and thawing, are included (III-3, 4), but #45 does not contain appreciable clay.

Several questions need to be answered in the expansive clay reaction: (1) Is there a difference in the species of clay minerals between dolomites and limestones? (2) Is the difference between expansion of dolomites and limestones of comparable clay contents largely textural? (3) If clay is the offender, why do graywackes, which are very rich in clay, not expand or deteriorate on weathering? (4) Is there a significant difference in the clay mineralogy between graywackes and carbonate rocks? (5) Why are many argillaceous dolomites perfectly stable?

## SERVICE FAILURES AND POSSIBLE FUTURE FAILURES

Mr. Paul Bird and Mr. George Toung, geologists for the N.Y.S.D.P.W., have been kind enough to indicate cases of concrete distress from coarse aggregate which have occurred in New York State (oral communication). Apparently these are the only aggregate failures in western New York State which are clearly not related to shale.

They are:

1. White or light-colored chert from Onondaga limestone, (#45 chert of Dunn and Ozol, 1962) "popouts" over each chert particle (Brockport area).
2. Thacher member (dolomitic part) of the Manlius formation, "popouts" over the Thacher* dolomite lithology (Syracuse area).
3. Lockport dolomite, Decew lithology, bridges, Rochester area; and highway, Clarendon area.
4. Beekmantown dolomite, St. Lawrence Seaway project, expansion of concrete.

**The latter two cases are not clear cut aggregate failures and are the subject to some disagreement in New York.**

Cases 2, 3, and 4 are all similar lithologies and failure could occur in any of them for three different reasons: (1) chemical reaction with liquids from portland cement paste (dedolomitization or other reactions), (2) wetting and drying alone, (3) freezing and thawing alone, or (4) combination of two or more. Failure 1, chert, could occur as a result of: (1) chemical reaction, (2) freezing and thawing alone,

*"Thacher" is according to Rickard (1962). Formerly Olney and Rondout.

or (3) a combination of the two. (A wet-dry failure seems unlikely but is not impossible in an alkaline environment.).

The similarity of the rocks with proven service failures in exposed concrete seems to be remarkable and more than coincidental. Even though the failures have not been studied systematically in the field as a part of this research, it is probably important to consider the group of similar characteristics which these units have and to consider some other rocks with similar characteristics. Field observations on example 4 (Beekmantown) were not possible because of flooding of the quarry.

The single characteristic which all of the above failures seem to have in common is expansive reactivity, either expansion by chemical reaction or by water absorption and expansion of clays.

In addition, they are characterized in 3 of 4 cases by freeze-thaw and/or wet-dry failures at quarry sites (the Beekmantown dolomite not observed), by rapid water absorption to critical saturation, by a strong tendency to retain absorbed water, by high water absorption, by high losses in soundness tests and by relatively high MgO and $Al_2O_3$ contents in the carbonate rocks. The two layers on which sonic velocities were taken had very low velocities

Two measurements seem to be most critical: (1) chemical reactivity and (2) water absorption-retention rates.

Several other rocks have this general group of characteristics and are suspect. These are: the somewhat dolomitic layers of the upper Pamelia formation (P-M-2, P-A-1 and P-B-2), and "C-unit" (C-1-1 and 2-C) and some of the Eramosa (1a) members of the Lockport formation and parts of the Elmwood-C (24-EC) and Clark Reservation (26-CR) member of the Manlius formation.

Failures of the above types (1, 2, 3, and 4) could have been prevented if the following things had been done:

1. Systematic geologic observations of the quarries involved in advance of use and testing. All of the poor rocks which could be observed in the field during this project (failures 1, 2, and 3), deteriorated by freezing and thawing and/or wetting and drying at the quarry sites. Photographs I-1, 2, and 3 show the nature of these failures.

2. Water absorption (rates and quantity) at atmospheric pressure and in a vacuum would have detected the inferior quality of failures 1, 2, and 3.

3. Tests of chemical reactivity would have detected failures 1 and 4.

4. Cases 1, 2 and 3 would have been detected by the freeze-thaw test. Case 4 (the Beekmantown) was not tested.

It should be noted, however, that the only way these failures could have been detected with assurance by any laboratory tests is by running tests on properly selected samples. The masking effect of "averaged samples" from stockpiles could miss all of the above cases. The most significant tests should be on a layer-by-layer basis on carefully described and subdivided material. In this way results are related to specific layers and quarrying operations can then be conducted so as to eliminate or minimize the effect of inferior zones. Fortunately the wet-dry test, the chemical reactivity tests, and the freeze-thaw tests can all be conducted quite satisfactorily on cored material; in fact, the sample used for wet-dry testing can later be used for either of the other tests.

Even though the information about the specific nature of the above failures is sketchy one thing seems to be striking: It is entirely possible that not a single failure is the result of porosity-permeability characteristics alone. Either chemical reactions or expansive clays may well have been critical in each case. It is also noteworthy that considering the wide range of porosities and absorptions of the rocks which have been studied, seemingly some should have failed in service as a clear result of simple freezing and thawing.

## DISCUSSION AND CONCLUSIONS

The principal internal factor influencing the rate of advance of an ice front in unidirectional freezing of saturated concrete or rock (the normal situation) is shown by thermal analysis to be the water content. The rate of ice advance is essentially inversely proportional to the water content. The quantity of water forced ahead of a moving ice front in saturated aggregate per unit time is essentially the same for all water contents over 1%.

The concept of "critical size" of aggregate is questioned because of the implication that larger, saturated natural rock outcrops should not exist in nature. The concept is questioned also because it does not seem reasonable that the force involved in getting 9% of the water out of a piece of aggregate at a relatively slow rate during freezing should be greater than the capillary pressure which drew the water into the particle relatively rapidly.

The aggregates which were tested include a wide range of water absorptions and pore size character and yet the only freeze-thaw failures which could be attributed to these lithologies are probably compounded by wetting-drying failures and chemical reactivity. These are expansive reactions and are believed to block pores of aggregate particles and entrap water. The water is then less able to leave the system and disruption occurs on freezing. When the reacting aggregates are

not highly absorptive, the products of reaction remain outside of the particles and disruption of concrete may occur as a result of this expansive stress without freezing and thawing.

## SUGGESTED TESTING PROCEDURES

The following procedures are believed to be more definitive than those currently in use and for the most part less expensive and more rapid:

1. Geologic description of individual layers or units in a quarry to be tested. Preferably the work should be done on 2-1/8" or larger cores. Particular attention should be paid to rocks which are "earthy" or "chalky" lustered, water-hungry (the tongue usually sticks to them), do not tend to outcrop and break up by conchoidal fractures on weathering. Outcrop logging should be systematically correlated with core logging. Shaly or soft rocks are eliminated automatically at this stage. Samples for testing should be taken by geologists and should consist of cores divided into samples which are the <u>full</u> intersected thickness of the described units.

2. All siliceous rocks, dolomitic or argillaceous rocks should be tested for chemical reactivity.

3. All rock units should be subjected to water absorption tests (24 hrs). An absorption of 0.5% or less indicates a very small likelihood of freeze-thaw sensitivity.

4. Rocks with absorptions of greater than 0.5% should be subjected to a "rate of absorption" test followed by vacuum saturation. (Rocks which absorb little or no additional water after 4 hours of vacuum should be subjected to the next test).

5. Rocks which tend to saturate rapidly can then be subjected to vacuum-drying to test their water retention. Rocks which tend to retain water, even under vacuum conditions, are very probably freeze-thaw sensitive.

Exact test limits and standardization of procedures are not here defined. However, even with the present state of knowledge, it is believed that the above procedures will detect all potentially unsound aggregate. Because cores are already available for all operating quarries in New York, the over-all procedures would be far less expensive than those currently in use.

# BIBLIOGRAPHY

ACI Committee 621 (1961), Selection and Use of Aggregates for Concrete, Jour. American Concrete Inst. Proc., Vol. 58, Nov.

Ahrens, T. J. and Katz, S., (1963), Ultrasonic Observation of the Calcite-Aragonite Transition, Jour. Geoph. Res., V. 68, No. 2, p. 529-537.

Banks, R. F. (1949), The Technology of Cement and Concrete, U.S. Dept. of the Interior Bureau of Reclamation.

Baxter, D. C. (1962), The Fusion Times of Slabs and Cylinders, J. of Ht. Trans., A.S.M.E., Series C. V. 84, No. 4, p. 317-326.

Beley, B. A. (1960), A Method of Heat Conduction Analysis of Melting and Solidifications Problems, J. Math. and Phys., V. 40, No. 4, p. 330-312.

Bisque, R. E. and Lemish, J. (1959), Insoluble Residue-Magnesium Content Relationship of Carbonate Rocks from the Devonian Cedar Valley Formation, J. Sed. Pet., V. 29, p. 73-76.

Bisque, R. E. and Lemish, J. (1958), Chemical Characteristics of Some Carbonate Aggregates as Related to the Durability of Concrete, Highway Res. Board Bull., 196.

Bisque, R. E. and Lemish, J. (1960), Silicification of Carbonate Aggregates in Concrete, Highway Res. Board Bull., 275.

Bloem, D. L. (1955), Soundness and Deleterious Substances, ASTM Spec. Tech. Pub., No. 169.

Bloem, D. L. (1956), Significance of Tests and Properties of Concrete and Aggregates, Special Tech. Pub. No. 169, Am. Soc. Testing Materials.

Birch, F. (1960), Velocity of Compressional Waves in Rocks to 10 Kilobars, Jour. Geophys. Res., Vol. 65, No. 4.

Birch, F. (1961), The Velocity of Compressional Waves in Rocks to 10 Kilobars, Jour. Geophys. Res., Vol. 66, No. 7.

Callan, E. J. (1954), The Thermal Properties of Mass Concrete vs. Influence by the Aggregates, Waterways Experiement Station Corps. of Engineers, U.S. Army Bull. 39.

BIBLIOGRAPHY
(2)

Callan, E. J. (1962), Thermal Expansion of Aggregates and Concrete Durability, Jour. Am. Conc. Inst., Feb.

Dunbar, C. O. and Rogers, J. (1957), Principles of Stratigraphy, John Wiley and Sons, New York, New York.

Dunn, J. R. (1961), The Geologic Control of Chemical and Physical Characteristics of Rock Raw Materials at Hudson Cement Company - Joint Meeting Industrial Minerals Division, CIM and SME-Ottawa, Canada.

Dunn, J. R. and Ozol, M., (1962), Deleterious Properties of Chert, N.Y.S.D.P.W., Eng. Res. Ser. RR-62-7.

Evans, G. W., Isachsen, E. and Mac Donald, J. K. L. (1950) Stefan Like Problems, Q. Appl. Math., V. 8, No. 3, p. 312-319.

Feldman, R. F. and Sereda, P. J. (1961), Characteristics of Sorption and Expansion Isotherms of Reactive Limestone Aggregate, Jour. Am. Conc. Inst., Vol. 58, p. 203-214.

Fisher, D. W., (1959), Correlation of the Silurian Rocks in New York State, N.Y.S. Geol. Survey.

Folk, R. L., (1959), Practical Petrographic Classification of Limestones, Bull. A.A.P.G., Vol. 43, p. 1-38.

Friedman, G. M. (1959), Identification of Carbonate Minerals by Staining Method, Jour. Sed. Pet., Vol. 29, No. 1.

Garrity, L. V. and Kreige, H. G. (1935), Studies of Accelerated Soundness Tests, Proceeding, Highway Res. Board, Vol. 15.

Geologic Characteristics of Stone Quarries, Phys. Res. Proj., No. 4, 1961, N.Y.S.D.P.W.

Geol. Soc. Am. (1951), Rock Color Charts.

Gray, J. E. (1957), A Rapid Method for Determining the Durability of Ledge Rock, Crushed Stone Jour., Sept.

Hadley, D. W. (1961), Alkali Reactivity of Carbonate Rocks - Expansion and Dedolomitization, Highway Res. Board Proc., Vol. 40.

Handbook of Chemistry and Physics (1960-1961), 42nd Edition Chemical Rubber Publishing Company.

Imbrie, J. and Poldervaart, A. (1959), Mineral Compositions Calculated from Chemical Analyses of Sedimentary Rocks, Jour. Sed. Pet., Vol. 29, No. 4, p. 588-595.

Kaufman, J. W., (1963), Correlation of Clay Mineralogy and Dolomitic Rocks, M. S. Thesis, Rensselaer Polytechnic Institute, Troy, New York.

Kennedy, T. B. and Mather, K. (1953), Correlation Between Laboratory Accelerated Freezing and Thawing and Weathering at Treat Island, Maine, October.

Lemish, J., Rush, F. E., and Hiltrop, C. L. (1958), Relationships of Physical Properties of Some Iowa Carbonate Aggregates to Durability of Concrete, Highway Res. Board, No. 196, p. 1-16.

Mather, K. and Silverman, J. W. (1954), The Petrography of Aggregates for Mass Concrete, 1954.

Miller, D. S. and Senechal, R. G. (1962), Physical and Chemical Investigation of the Catskill Argillaceous Sandstone, Report Available Rensselaer Department of Geology.

Mohammed, M. (1963), Physical-Chemical Characteristics of Some Carbonate Aggregates from Central and Western New York, Masters Thesis, Geology Department, Rensselaer Polytechnic Institute.

Ostrom, M. E. (1961), Separation of Clay Minerals from Carbonate Rocks by Using Acid, Jour. Sed. Pet., Vol. 31, No. 1.

Ozol, M. (1963), Alkali Reactivity of Cherts and Stratigraphy and Petrology of Cherts and Associated Limestones of the Onondaga Formation of Central and Western New York, Doctor of Philosophy Thesis, Geology Department, Rensselaer Polytechnic Institute.

Pearson, J. C. (1941), Concrete Failure Attributed to Aggregate of Low Thermal Coefficient, Jour. Am. Conc. Inst., Sept.

Pounder, E. R. and Stalinski, P. (1960), General Properties of Arctic Sea Ice (In: Intl. Assoc. of Scientific Hydrology, Snow and Ice Commission, General Assembly of Helsinki, 25-7-6-8.

Powers, T. C. (1955), Basic Considerations Pertaining to Freezing and Thawing Tests, Proceedings American Society for Testing Materials.

Public Works Specifications (1957), State of New York, Department of Public Works.

Rice, J. M., A Rapid Method for Determining the Resistance of Ledge Rock to Freezing, Proc. of Ninth Ann. Sym. on Geology as Applied to HYW. Eng., p. 23-30.

Rickard, L. V. (1962), Late Cayugan and Helderbergian Stratigraphy in New York, N.Y.S. Museum and Science Service, Bull. No. 386.

Robertson, E. C. (1959), Physical Properties of Limestone and Dolomite Cores from the Sandhill Well, Weed County, West Virginia, (In: A Symposium on the Sandhill Deep Well: West Virginia Geol. and Survey, Report No. 18, 114-144), 1959.

Rosenholtz, J. L. and Smith, D. T. (1949), Linear Thermal Expansion of Calcite, Var. Iceland Spar, and Yule Marble, Am. Min., Vol. 34.

Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregates, A.S.T.M. Designation: C 127-59. Supplement Book of A.S.T.M. Standards 1959.

Swenson, E. G. and Gillott, J. E. (1960), Characteristics of Kingston Carbonate Rock Reaction, Highway Res. Board Bull. 275.

Todd, D. K. (1959), Ground Water Hydrology, John Wiley and Sons, Inc.

Verbeck, G. and Landgren, R. (1960), Influence of Physical Characteristics of Aggregates on Frost Resistance of Concrete. Am. Soc. for Testing Materials Proc., Vol. 60, p. 1063.

Warshaw, C. M. and Roy, R. (1961), Classification and a Scheme for the Identification of Layer Silicates, Geol. Soc. Am. Bull., Vol. 72, p. 1455.

## APPENDICES

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# APPENDIX A

## TABLES

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Table A-1
Chemical Analyses
(1)

| Sample | Moisture | Loss on Ignition | Insol. Matter | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $TiO_2$ | CaO | MgO | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 37-B | 0.16 | 35.48 | 1.58 | 12.38 | 4.41 | 0.11 | 0.04 | 41.00 | 3.31 | 0.04 | 1.25 |
| 42 | 0.12 | 36.26 | 1.36 | 10.86 | 3.86 | 0.11 | 0.05 | 42.60 | 3.05 | 0.04 | 1.56 |
| 50 | 0.08 | 34.18 | 2.13 | 10.78 | 2.85 | 0.38 | 0.15 | 41.40 | 7.14 | 0.13 | 0.12 |
| 42-PB | 0.24 | 42.44 | 0.70 | 2.40 | 0.29 | 0.43 | 0.04 | 51.70 | 1.95 | 0.05 | 0.20 |
| 42-J-0 | 0.12 | 42.66 | 0.54 | 1.06 | 0.35 | 0.32 | 0.03 | 53.00 | 1.50 | 0.04 | 0.23 |
| J-V | 0.02 | 43.51 | 0.10 | 0.76 | 0.31 | 0.16 | 0.05 | 47.13 | 8.21 | 0.02 | 0.23 |
| EB-1 | 0.12 | 41.61 | 1.74 | 2.42 | 0.54 | 0.43 | 0.03 | 52.08 | 1.39 | 0.17 | 0.30 |
| EA-1 | 0.09 | 42.56 | 0.60 | 1.00 | 0.31 | 0.25 | 0.04 | 53.47 | 0.74 | 0.11 | 0.15 |
| 35-J-1 | 0.11 | 41.83 | 1.70 | 0.56 | 0.06 | 0.21 | 0.03 | 54.17 | 0.96 | 0.02 | 0.32 |
| 42-J-1 | 0.08 | 42.37 | 0.96 | 2.42 | 0.88 | 0.24 | 0.06 | 49.85 | 3.66 | 0.06 | 0.36 |
| 35-1 | 0.06 | 42.01 | 1.88 | 0.56 | 0.10 | 0.27 | 0.03 | 53.68 | 0.99 | 0.06 | 0.21 |
| 34-J | 0.12 | 41.44 | 0.28 | 3.88 | 0.44 | 0.22 | 0.02 | 52.65 | 0.98 | 0.03 | 0.17 |
| 26-J | 0.20 | 42.46 | 0.63 | 1.60 | 0.17 | 0.27 | 0.02 | 53.60 | 0.92 | 0.04 | 0.31 |
| 24-J | 0.05 | 42.46 | 1.10 | 1.56 | 0.35 | 0.32 | 0.03 | 53.09 | 1.20 | 0.04 | 0.21 |
| 42-CR | 1.52 | 41.24 | 0.44 | 1.42 | 0.67 | 0.32 | 0.05 | 51.70 | 2.24 | 0.03 | 0.34 |
| OL-1-1 | 0.07 | 37.38 | 0.72 | 12.26 | 0.43 | 0.57 | 0.04 | 47.34 | 0.38 | 0.02 | 0.12 |
| CR | 0.00 | 43.20 | 0.20 | 1.26 | 0.26 | 0.26 | 0.04 | 48.81 | 4.86 | 0.02 | 0.24 |
| 35-CR | 0.2 | 41.52 | 1.78 | 0.50 | 0.27 | 0.32 | 0.03 | 53.22 | 1.16 | 0.03 | 0.32 |
| 34-3 | 0.12 | 40.36 | 1.16 | 5.22 | 1.13 | 0.48 | 0.07 | 48.49 | 2.81 | 0.09 | 0.02 |
| 26-CR | 0.18 | 36.32 | 2.62 | 11.36 | 3.02 | 1.30 | 0.16 | 34.60 | 9.72 | 0.09 | 1.29 |
| 24-CR | 0.05 | 39.76 | 1.98 | 4.80 | 1.54 | 1.28 | 0.08 | 43.51 | 6.10 | 0.04 | 0.15 |
| 42-ECX | 0.08 | 43.12 | 0.22 | 1.06 | 0.72 | 0.24 | 0.04 | 52.65 | 2.00 | 0.02 | 0.25 |
| 42-ECY | 0.08 | 37.32 | 1.48 | 5.24 | 3.46 | 1.01 | 0.05 | 47.45 | 3.05 | 0.02 | 0.30 |
| R-1-1 | 0.08 | 38.70 | 3.24 | 9.38 | 2.76 | 0.28 | 0.14 | 33.70 | 11.44 | 0.08 | 0.15 |

Table A-1
Chemical Analyses
(2)

| Sample | Moisture | Loss on Ignition | Insol. Matter | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $TiO_2$ | CaO | MgO | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 34-EC(1) | 0.00 | 39.96 | 1.60 | 6.28 | 1.36 | 0.89 | 0.03 | 43.40 | 6.02 | 0.02 | 0.80 |
| 34-EC(2) | 0.11 | 40.87 | 2.04 | 6.46 | 0.83 | 0.64 | 0.07 | 41.63 | 7.68 | 0.10 | 0.11 |
| 26-EC | 0.08 | 41.66 | 1.12 | 2.62 | 0.17 | 0.27 | 0.02 | 52.35 | 1.27 | 0.01 | 0.30 |
| 24-EC | 0.11 | 40.77 | 2.16 | 5.32 | 0.92 | 0.43 | 0.05 | 45.60 | 4.92 | 0.12 | 0.05 |
| 34-EB | 1.92 | 37.38 | 1.84 | 7.04 | 1.86 | 1.19 | 0.07 | 46.48 | 1.60 | 0.02 | 0.30 |
| 26-EB | 0.14 | 40.00 | 0.26 | 6.96 | 0.34 | 0.32 | 0.04 | 51.70 | 0.88 | 0.03 | 0.19 |
| E-2 | 0.28 | 40.44 | 1.20 | 6.04 | 0.26 | 0.48 | 0.04 | 49.71 | 1.97 | 0.08 | 0.28 |
| 24-EB | 0.00 | 40.88 | 1.02 | 4.76 | 0.55 | 0.65 | 0.02 | 49.40 | 2.34 | 0.02 | 0.30 |
| 34-EA | 0.20 | 39.54 | 1.32 | 4.94 | 1.34 | 0.64 | 0.08 | 50.01 | 0.72 | 0.06 | 1.12 |
| 26-EA | 0.00 | 41.16 | 0.50 | 4.78 | 0.31 | 0.43 | 0.02 | 51.40 | 1.09 | 0.03 | 0.14 |
| 24-EA | 0.06 | 40.08 | 2.42 | 6.30 | 0.80 | 0.64 | 0.08 | 41.43 | 7.73 | 0.03 | 0.42 |
| Asr-1 | 0.10 | 38.70 | 13.32 | 10.98 | 2.49 | 1.06 | 0.03 | 24.20 | 17.78 | 0.02 | 1.72 |
| OL-2 | 0.12 | 41.95 | 1.34 | 2.62 | 0.39 | 0.43 | 0.03 | 51.94 | 1.07 | 0.05 | 0.18 |
| 34-1 | 0.08 | 41.63 | 1.74 | 2.68 | 0.44 | 0.43 | 0.03 | 51.52 | 1.12 | 0.07 | 0.07 |
| 24-OL | 0.10 | 41.48 | 0.74 | 2.78 | 0.42 | 0.43 | 0.03 | 52.40 | 1.19 | 0.02 | 0.30 |
| OZ | 0.00 | 36.72 | 0.92 | 13.18 | 0.67 | 1.02 | 0.05 | 42.95 | 3.52 | 0.03 | 0.41 |
| R2 | 0.07 | 42.49 | 1.06 | 3.24 | 0.31 | 0.37 | 0.03 | 47.34 | 5.52 | 0.07 | 0.24 |
| 26-OL | 0.18 | 41.64 | 0.52 | 2.36 | 0.27 | 0.43 | 0.04 | 52.95 | 0.99 | 0.04 | 0.16 |
| OD | 0.02 | 38.38 | 3.16 | 11.10 | 2.63 | 1.19 | 0.12 | 25.70 | 17.15 | 0.02 | 0.47 |
| RA | 0.00 | 37.28 | 3.54 | 11.32 | 2.63 | 1.19 | 0.10 | 25.42 | 16.59 | 0.05 | 1.55 |
| RB | 0.00 | 43.04 | 0.98 | 4.28 | 0.50 | 0.65 | 0.05 | 37.78 | 11.65 | 0.04 | 1.02 |
| Asr-3 | 0.04 | 41.98 | 2.18 | 6.10 | 1.73 | 0.64 | 0.03 | 28.78 | 17.94 | 0.03 | 0.90 |
| K-3-b | 0.14 | 41.34 | 0.60 | 4.68 | 1.71 | 0.17 | 0.06 | 36.21 | 13.80 | 0.03 | 0.57 |
| K-3-a | 0.16 | 38.80 | 1.14 | 8.22 | 2.60 | 0.15 | 0.09 | 32.73 | 15.22 | 0.02 | 0.52 |
| K-2 | 0.05 | 43.14 | 0.60 | 3.64 | 2.71 | 0.23 | 0.06 | 38.01 | 12.47 | 0.04 | 0.45 |
| Ib | 0.10 | 46.57 | 0.64 | 0.28 | 0.27 | 0.37 | 0.02 | 31.27 | 20.99 | 0.06 | 0.19 |

Table A-1
Chemical Analyses
(3)

| Sample | Moist-ure | Loss on Ignition | Insol. Matter | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $TiO_2$ | CaO | MgO | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6c-2 | 0.06 | 44.19 | 0.44 | 3.54 | 2.87 | 0.12 | 0.03 | 28.90 | 20.40 | 0.08 | 0.46 |
| 6c-1 | 0.06 | 43.64 | 1.16 | 4.10 | 0.64 | 0.93 | 0.05 | 29.88 | 20.01 | 0.04 | 0.29 |
| 7b | 0.22 | 43.04 | 0.26 | 5.84 | 1.43 | 0.52 | 0.01 | 28.80 | 19.81 | 0.02 | 0.62 |
| 8c | 0.00 | 46.30 | 0.24 | 0.84 | 0.36 | 0.27 | 0.03 | 31.10 | 20.33 | 0.03 | 0.11 |
| 8b | 0.00 | 47.10 | 0.06 | 0.00 | 0.14 | 0.32 | 0.04 | 31.30 | 21.08 | 0.03 | 0.05 |
| 8a | 0.05 | 46.31 | 1.00 | 0.08 | 0.39 | 0.18 | 0.03 | 31.55 | 21.00 | 0.05 | 0.06 |
| 1a | 0.22 | 38.42 | 0.86 | 10.52 | 4.49 | 0.21 | 0.02 | 25.26 | 17.89 | 0.04 | 1.65 |
| 2e | 0.14 | 44.22 | 0.18 | 4.00 | 0.72 | 0.64 | 0.38 | 28.74 | 20.02 | 0.03 | 1.02 |
| 2du | 0.12 | 41.93 | 0.54 | 6.64 | 0.98 | 1.39 | 0.35 | 29.17 | 17.39 | 0.02 | 1.24 |
| 2d1 | 0.02 | 45.72 | 0.94 | 0.76 | 0.70 | 0.13 | 0.05 | 31.82 | 20.15 | 0.10 | 0.13 |
| 4c | 0.08 | 40.53 | 0.96 | 10.92 | 2.34 | 0.27 | 0.07 | 26.20 | 18.52 | 0.01 | 0.53 |
| 6b | 0.14 | 26.12 | 2.94 | 34.04 | 5.40 | 0.32 | 0.06 | 17.50 | 11.78 | 0.02 | 1.05 |
| 6a | 0.32 | 31.50 | 1.82 | 25.72 | 4.15 | 0.53 | 0.04 | 21.29 | 14.12 | 0.02 | 0.64 |
| 7a | 0.05 | 14.26 | 12.02 | 53.58 | 0.43 | 2.28 | 0.09 | 10.08 | 6.67 | 0.03 | 0.74 |
| 9 | 0.18 | 19.47 | 0.54 | 54.90 | 2.06 | 0.43 | 0.33 | 13.25 | 8.78 | 0.01 | 0.35 |
| 2c | 0.08 | 40.84 | 1.78 | 6.42 | 2.42 | 0.66 | 0.10 | 27.77 | 19.06 | 0.07 | 0.71 |
| C-1-1 | 0.18 | 39.58 | 1.18 | 9.56 | 2.90 | 0.85 | 0.15 | 27.01 | 17.45 | 0.07 | 0.12 |
| 2c-reef | 0.12 | 46.33 | 0.32 | 0.26 | 0.02 | 0.73 | 0.05 | 31.89 | 20.88 | 0.04 | 0.03 |
| 2b | 0.10 | 43.07 | 1.54 | 0.96 | 0.34 | 1.59 | 0.05 | 31.27 | 19.21 | 0.03 | 0.41 |
| 3b | 0.18 | 46.42 | 0.38 | 0.42 | 0.16 | 0.79 | 0.05 | 31.27 | 21.14 | 0.06 | 0.03 |
| 4b | 0.11 | 44.99 | 0.38 | 1.90 | 0.45 | 1.09 | 0.04 | 30.50 | 20.62 | 0.09 | 0.22 |
| 5b | 0.03 | 33.31 | 2.64 | 19.00 | 1.92 | 0.06 | 1.08 | 34.36 | 6.58 | 0.08 | 0.49 |
| DQ-1-1 | 0.16 | 41.33 | 1.70 | 7.44 | 1.04 | 1.38 | 0.08 | 30.77 | 15.96 | 0.14 | 0.31 |
| 2a | 0.15 | 38.34 | 1.74 | 9.76 | 0.49 | 2.02 | 0.15 | 29.88 | 16.35 | 0.10 | 0.08 |
| 4a | 0.14 | 32.65 | 2.24 | 22.65 | 1.79 | 2.39 | 0.14 | 22.93 | 15.02 | 0.06 | 1.00 |
| 5a | 0.04 | 40.59 | 1.96 | 7.20 | 3.08 | 0.37 | 0.12 | 29.18 | 17.24 | 0.08 | 0.53 |

Table A-1
Chemical Analyses
(4)

| Sample | Moisture | Loss on Ignition | Insol. Matter | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $TiO_2$ | CaO | MgO | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P-B-2 | 0.13 | 27.86 | 6.90 | 25.90 | 3.29 | 1.17 | 0.20 | 31.05 | 3.15 | 0.18 | 0.12 |
| P-B-1 | 0.09 | 42.07 | 1.48 | 1.34 | 0.79 | 0.32 | 0.03 | 52.64 | 0.62 | 0.10 | 0.22 |
| P-A-2 | 0.13 | 32.92 | 3.84 | 15.48 | 3.36 | 0.42 | 0.16 | 41.79 | 0.76 | 0.25 | 0.13 |
| P-A-1 | 0.17 | 25.41 | 6.08 | 32.24 | 3.58 | 1.17 | 0.19 | 24.79 | 5.71 | 0.43 | 0.98 |
| P-M-3 | 0.12 | 26.54 | 3.12 | 27.34 | 5.55 | 2.52 | 0.27 | 29.62 | 3.12 | 0.30 | 2.48 |
| P-M-2 | 0.02 | 36.55 | 0.92 | 11.10 | 1.64 | 2.29 | 0.13 | 44.18 | 2.17 | 0.09 | 0.63 |
| P-M-1 | 0.00 | 41.82 | 0.12 | 2.36 | 1.52 | 0.21 | 0.03 | 43.48 | 9.36 | 0.04 | 0.27 |
| SLS-G | 0.00 | 41.34 | 2.12 | 6.62 | 1.53 | 0.77 | 0.08 | 27.27 | 18.78 | 0.02 | 1.19 |
| 40-30 | | | | 75.80 | 9.90 | 1.52 | | 3.00 | 0.72 | 0.29 | 0.36 |
| 68-6R | | | | 74.20 | 12.32 | 4.69 | | 1.00 | 1.30 | 0.79 | 2.20 |
| 9-14-13R | | | | 74.00 | 12.32 | 2.88 | | 1.40 | 1.23 | 1.35 | 1.57 |
| 9-14-211 | | | | 75.80 | 11.01 | 2.22 | | 1.60 | 1.09 | 1.17 | 1.64 |
| 9-14-212 | | | | 77.40 | 9.90 | 4.70 | | 1.40 | 1.01 | 1.00 | 1.58 |

## Table A-2

## Normative Analyses
(1)

| | Carbonates | | | Clays* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Cal. | Dol. | Total | Ill. | Ser. | Fer-Ser | Chl. | Mont. | Total | Quartz | Minor Constits. | Insol. Residue |
| 37-B | 65.09 | 13.93 | 79.02 | 6.22 | 7.08 | 0.0 | 0.0 | 0.0 | 13.30 | 5.79 | 1.13 | 18.52 |
| 42 | 69.15 | 11.83 | 80.98 | 10.89 | 7.08 | 0.0 | 0.0 | 0.0 | 17.97 | 1.90 | 1.08 | 16.24 |
| 50 | 69.80 | 6.87 | 76.67 | 1.81 | 0.0 | 0.0 | 19.22 | 0.0 | 21.03 | 4.96 | 1.83 | 16.29 |
| 42-PB | 88.32 | 7,12 | 95.43 | 0.0 | 0.10 | 1.7 | 1.36 | 0.0 | 3.17 | 1.77 | 0.77 | 3.86 |
| 42-J-C | 92.45 | 3.77 | 96.22 | 0.0 | 0.91 | 1.11 | 2.33 | 0.0 | 4.35 | 0.0 | 0.58 | 2.30 |
| J-V | 69.57 | 26.63 | 96.20 | 0.0 | 1.70 | 0.26 | 8.25 | 0.0 | 10.21 | 0.0 | 0.53 | 1.38 |
| EA-1 | 94.36 | 1.80 | 96.16 | 0.0 | 0.67 | 0.74 | 1.20 | 0.0 | 2.60 | 0.0 | 1.28 | 2.20 |
| BB-1 | 91.51 | 2.44 | 93.95 | 0.0 | 1.0 | 1.70 | 2.96 | 0.0 | 5.62 | 0.36 | 1.80 | 5.16 |
| 35-J-1 | 94.66 | 0.0 | 94.66 | 0.0 | 2.72 | 0.53 | 3.32 | 0.0 | 6.57 | 0.0 | 0.48 | 2.56 |
| 42-J-1 | 81.75 | 13.02 | 94.77 | 0.0 | 2.40 | 0.67 | 2.81 | 0.0 | 5.90 | 0.38 | 0.93 | 4.56 |
| 35-1 | 95.06 | 0.0 | 95.06 | 0.0 | 0.99 | 0.85 | 3.42 | 0.0 | 5.25 | 0.0 | 0.82 | 2.84 |
| 34-J | 93.77 | 0.0 | 93.77 | 0.0 | 0.90 | 0.58 | 3.39 | 0.0 | 4.86 | 2.57 | 0.60 | 4.84 |
| 26-J | 95.08 | 0.93 | 96.01 | 0.0 | 1.83 | 0.85 | 2.48 | 0.0 | 5.16 | 0.00 | 0.85 | 2.68 |
| 24-J | 53.45 | 34.91 | 88.35 | 1.51 | 0.0 | 0.0 | 0.64 | 4.09 | 6.23 | 2.21 | 1.00 | 10.74 |
| 42-CR | 90.97 | 2.16 | 93.13 | 2.32 | 1.84 | 1.11 | 6.11 | 0.0 | 9.06 | 0.0 | 0.65 | 11.32 |
| CL-1-1 | 84.23 | 0.28 | 84.51 | 1.85 | 0.0 | 0.0 | 0.84 | 0.0 | 2.69 | 11.05 | 0.76 | 14.76 |
| CR | 76.28 | 19.80 | 96.08 | 0.0 | 1.29 | 0.79 | 1.84 | 0.0 | 3.92 | 0.16 | 0.51 | 2.02 |
| 35-CR | 93.95 | 0.0 | 93.95 | 0.0 | 1.67 | 1.11 | 4.01 | 0.0 | 6.79 | 0.0 | 0.59 | 2.90 |
| 34-3 | 81.42 | 9.12 | 90.53 | 0.30 | 0.0 | 0.0 | 2.78 | 0.33 | 3.41 | 3.81 | 1.25 | 8.08 |
| 26-CR | 40.63 | 38.23 | 78.86 | 0.0 | 4.98 | 6.36 | 4.71 | 0.0 | 16.05 | 7.57 | 1.52 | 18.46 |
| 24-CR | 64.92 | 23.06 | 87.98 | 2.26 | 0.0 | 0.0 | 3.33 | 1.36 | 6.95 | 2.05 | 0.86 | 9.68 |
| 42-ECX | 90.07 | 6.92 | 97.00 | 0.0 | 1.47 | 0.69 | 1.68 | 0.0 | 3.84 | 0.0 | 0.56 | 2.28 |
| 42-ECY | 84.13 | 0.25 | 84.38 | 4.52 | 0.0 | 0.0 | 9.69 | 0.0 | 14.21 | 0.74 | 0.87 | 11.24 |
| R-1-1 | 32.06 | 51.11 | 83.17 | 2.26 | 0.0 | 0.0 | 0.59 | 6.15 | 9.00 | 3.55 | 1.39 | 15.80 |
| 34-EC(1) | 64.11 | 24.22 | 88.33 | 0.0 | 2.88 | 4.16 | 2.50 | 0.0 | 9.55 | 4.32 | 0.62 | 12.00 |
| 34-EC(2) | 55.83 | 33.76 | 89.59 | 1.66 | 0.0 | 0.0 | 0.79 | 0.85 | 3.30 | 4.41 | 1.28 | 10.04 |

## Table A-2
## Normative Analyses
## (2)

| | Carbonates | | | Clays* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Cal. | Dol. | Total | Ill. | Ser. | Fer-Ser. | Chl. | Mont. | Total | Quartz | Minor Constits. | Insol. Residue |
| 26-EC | 92.44 | 1.69 | 94.12 | 0.0 | 1.75 | 0.85 | 3.12 | 0.0 | 5.71 | 1.10 | 0.40 | 4.20 |
| 24-EC | 70.21 | 20.30 | 90.51 | 0.75 | 0.0 | 0.0 | 1.56 | 0.44 | 2.74 | 3.68 | 1.44 | 8.80 |
| 34-EB | 80.87 | 3.38 | 84.25 | 4.52 | 0.0 | 0.0 | 2.31 | 1.29 | 8.12 | 3.47 | 0.71 | 12.00 |
| 26-EB | 90.49 | 0.0 | 90.49 | 0.0 | 0.57 | 1.11 | 3.04 | 0.0 | 4.72 | 5.87 | 0.61 | 7.92 |
| E-2 | 85.61 | 5.56 | 91.18 | 0.0 | 0.53 | 1.97 | 2.60 | 0.0 | 5.11 | 4.77 | 1.02 | 8.01 |
| 24-EB | 83.60 | 8.19 | 91.79 | 0.0 | 0.0 | 2.88 | 1.90 | 0.0 | 4.78 | 4.24 | 0.52 | 7.00 |
| 34-EA | 88.66 | 0.72 | 89.39 | 14.41 | 2.07 | 0.0 | 0.0 | 0.0 | 16.48 | 0.0 | 1.01 | 8.32 |
| 26-EA | 90.16 | 2.74 | 92.90 | 0.0 | 0.0 | 1.7 | 1.70 | 0.0 | 3.40 | 4.24 | 0.58 | 6.04 |
| 24-EA | 56.92 | 31.10 | 88.02 | 0.0 | 0.92 | 2.83 | 3.22 | 0.0 | 6.96 | 5.02 | 0.70 | 10.24 |
| Asr-1 | 0.0 | 85.34 | 85.34 | 0.0 | 0.0 | 0.0 | 0.0 | 14.62 | 14.62 | 4.20 | 0.82 | 17.88 |
| OL-2 | 90.27 | 4.29 | 94.56 | 0.0 | 0.0 | 1.70 | 0.46 | 0.0 | 2.16 | 2.23 | 0.77 | 4.81 |
| 34-1 | 89.49 | 4.34 | 93.83 | 1.06 | 0.0 | 0.0 | 0.44 | 0.25 | 1.74 | 1.54 | 0.94 | 5.32 |
| 24-OL | 92.97 | 0.82 | 93.79 | 0.0 | 0.95 | 1.70 | 3.50 | 0.0 | 6.15 | 1.48 | 0.52 | 4.40 |
| OZ | 70.02 | 11.99 | 82.01 | 0.0 | 0.0 | 4.86 | 3.10 | 0.0 | 7.96 | 12.34 | 0.65 | 15.84 |
| R 2 | 72.64 | 21.67 | 94.30 | 0.0 | 0.74 | 1.38 | 2.71 | 0.0 | 4.83 | 1.91 | 0.93 | 5.01 |
| 26-OL | 94.22 | 0.0 | 94.22 | 0.0 | 0.0 | 1.70 | 3.42 | 0.0 | 5.12 | 1.39 | 0.68 | 3.62 |
| OD | 4.26 | 76.05 | 80.31 | 7.09 | 0.0 | 0.0 | 0.76 | 3.22 | 11.07 | 5.24 | 0.85 | 18.20 |
| RA | 5.76 | 72.36 | 78.12 | 19.26 | 2.98 | 0.0 | 0.0 | 0.0 | 22.24 | 0.52 | 1.08 | 18.78 |
| RB | 37.22 | 55.82** | 93.04 | 0.0 | 8.62 | 0.0 | 0.0 | 0.0 | 8.62 | 0.15 | 0.72 | 6.46 |
| Asr-3 | 6.78 | 81.72 | 89.50 | 1.70 | 6.61 | 0.0 | 0.0 | 1.13 | 9.44 | 1.23 | 0.74 | 10.68 |
| K-3-b | 35.23 | 53.72 | 88.95 | 0.0 | 4.53 | 0.31 | 7.11 | 0.0 | 11.95 | 0.93 | 0.77 | 7.22 |
| K-2 | 37.47 | 55.43 | 92.90 | 6.79 | 0.0 | 0.0 | 0.22 | 0.0 | 7.00 | 0.0 | 0.91 | 6.70 |
| K-3-a | 28.40 | 54.69 | 83.09 | 7.84 | 0.0 | 0.0 | 10.13 | 0.0 | 17.96 | 1.94 | 0.81 | 12.20 |
| 1b | 6.01 | 91.60 | 97.61 | 0.0 | 0.32 | 1.38 | 3.33 | 0.0 | 5.03 | 0.0 | 0.83 | 1.58 |
| 6c-1 | 3.67 | 87.62 | 91.28 | 6.94 | 0.0 | 0.0 | 3.28 | 0.0 | 10.21 | 0.0 | 1.29 | 7.00 |
| 6c-2 | 6.38 | 86.27 | 92.65 | 0.0 | 0.0 | 4.38 | 3.97 | 0.0 | 8.35 | 3.01 | 0.73 | 6.88 |
| 7b | 4.97 | 85.16 | 90.13 | 0.0 | 3.21 | 2.18 | 4.12 | 0.0 | 9.51 | 3.39 | 0.81 | 8.06 |

## Table A-2
## Normative Analyses
## (3)

| Sample | Carbonates | | | Clays* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cal. | Dol. | Total | Ill. | Ser. | Fer-Ser. | Chl. | Mont. | Total | Quartz | Minor Constits. | Insol. Residue |
| 8c | 5.99 | 91.05 | 97.04 | 0.0 | 0.14 | 0.85 | 1.47 | 0.0 | 2.45 | 0.29 | 0.60 | 1.74 |
| 8b | 4.93 | 93.70 | 98.63 | 0.81 | 0.0 | 0.0 | 1.94 | 0.0 | 2.76 | 0.0 | 0.58 | 0.56 |
| 8a | 7.57 | 89.62 | 97.19 | 0.91 | 0.0 | 0.0 | 4.73 | 0.0 | 5.64 | 0.0 | 0.77 | 1.68 |
| 1a | 2.21 | 78.03 | 80.23 | 19.92 | 3.00 | 0.0 | 0.0 | 0.0 | 22.92 | 0.0 | 1.12 | 15.10 |
| 2e | 2.22 | 90.16 | 92.39 | 7.90 | 4.57 | 0.0 | 0.0 | 0.0 | 12.47 | 0.0 | 0.99 | 5.92 |
| 2du | 8.91 | 79.20 | 88.11 | 1.74 | 9.51 | 0.0 | 0.0 | 0.0 | 11.25 | 1.34 | 0.90 | 9.90 |
| 2dl | 9.81 | 86.31 | 96.13 | 0.0 | 1.01 | 0.10 | 4.42 | 0.0 | 5.53 | 0.0 | 1.25 | 2.58 |
| 4c | 1.10 | 83.57 | 84.67 | 5.84 | 1.21 | 0.0 | 0.0 | 0.0 | 7.05 | 6.96 | 0.68 | 14.56 |
| 6b | 2.29 | 52.18 | 54.47 | 10.86 | 2.79 | 0.0 | 0.0 | 0.0 | 13.65 | 24.69 | 1.09 | 42.76 |
| 6a | 3.84 | 62.02 | 65.86 | 9.65 | 0.0 | 0.0 | 0.52 | 0.0 | 10.17 | 17.72 | 0.93 | 32.26 |
| 7a | 3.81 | 25.92 | 29.74 | 0.0 | 0.0 | 11.60 | 3.46 | 0.0 | 15.06 | 52.66 | 0.67 | 68.40 |
| 9 | 2.94 | 37.65 | 40.59 | 0.0 | 5.6 | 1.7 | 1.9 | 0.0 | 9.20 | 51.90 | 0.91 | 58.26 |
| c-1-1 | 6.15 | 76.83 | 82.97 | 1.81 | 0.0 | 0.0 | 1.99 | 6.82 | 10.62 | 3.41 | 1.33 | 14.64 |
| 2c | 6.09 | 79.51 | 85.61 | 0.0 | 3.27 | 2.93 | 5.79 | 0.0 | 11.99 | 3.29 | 1.23 | 11.38 |
| 2c-reef | 8.82 | 88.51 | 97.33 | 0.52 | 0.0 | 0.0 | 5.22 | 0.0 | 5.74 | 0.0 | 1.08 | 1.38 |
| 2b | 9.40 | 85.33 | 94.73 | 0.0 | 0.0 | 7.91 | 1.92 | 0.0 | 9.82 | 3.73 | 0.62 | 4.43 |
| 3b | 6.37 | 90.95 | 97.32 | 0.49 | 0.0 | 0.0 | 4.27 | 0.0 | 4,76 | 0.0 | 1.4 | 1.80 |
| 4b | 6.81 | 87.55 | 94.36 | 0.0 | 0.0 | 5.23 | 5.11 | 0.0 | 10.35 | 0.28 | 1.13 | 3.86 |
| 5b | 47,20 | 25.86 | 73.07 | 0.0 | 1.71 | 2.61 | 3.20 | 0.0 | 7.52 | 17.97 | 1.24 | 25.14 |
| 2a | 19.71 | 61.73 | 81.44 | 1.21 | 0.0 | 0.0 | 9.69 | 0.0 | 10.89 | 6.48 | 3.16 | 14.15 |
| DQ-1-1 | 15.98 | 71.44 | 87.41 | 4.91 | 0.0 | 0.0 | 0.49 | 0.0 | 5.4 | 4.04 | 2.01 | 11.64 |
| 4a | 7.58 | 60.99 | 68.57 | 0.0 | 0.0 | 12.19 | 5.83 | 0.0 | 18.01 | 20.66 | 1.12 | 28.82 |
| 5a | 11.56 | 73.96 | 85.51 | 7.99 | 0.0 | 0.0 | 2.53 | 0.0 | 10.52 | 2.14 | 1.40 | 12.73 |
| P-B-2 | 48.28 | 12.41 | 60.69 | 1.81 | 0.0 | 0.0 | 1.25 | 9.29 | 12.35 | 17.70 | 2.35 | 37.46 |
| P-B-1 | 92.41 | 2.57 | 94.98 | 1.37 | 1.09 | 0.0 | 0.0 | 0.0 | 2.46 | 0.0 | 1.24 | 3.96 |
| P-A-2 | 73.96 | 0.40 | 74.36 | 1.96 | 0.0 | 0.0 | 2.04 | 5.98 | 9.98 | 8.65 | 2.91 | 23.26 |
| P-A-1 | 30.31 | 24.88 | 55.19 | 6.36 | 4.72 | 0.0 | 0.0 | 0.0 | 11.08 | 24.38 | 4.49 | 43.26 |

## Table A-2
## Normative Analyses
## (4)

| | Carbonates | | | Clays* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Cal. | Dol. | Total | Ill. | Ser. | Fer-Ser. | Chl. | Mont.- | Total | Quartz | Minor Constits. | Insol. Residue |
| P-M-3 | 44.57 | 14.11 | 58.68 | 0.83 | 3.59 | 0.0 | 0.0 | 17.47 | 21.89 | 12.47 | 3.68 | 38.80 |
| P-M-2 | 74.59 | 7.42 | 82.01 | 10.05 | 0.0 | 0.0 | 0.49 | 0.0 | 10.54 | 5.65 | 1.46 | 16.08 |
| P-M-1 | 60.13 | 31.79 | 91.92 | 4.07 | 0.0 | 0.0 | 7.73 | 0.0 | 11.80 | 0.0 | 0.81 | 4.24 |
| SLS G | 3.36 | 83.08 | 86.44 | 15.71 | 1.95 | 0.0 | 0.0 | 0.0 | 17.66 | 0.0 | 0.69 | 11.12 |
| Av. Grwk. | 0.00 | 5.14** | 5.14 | 22.16 | 0.0 | 0.0 | 0.0 | 27.10 | 49.27 | 41.90 | 9.25 | 91.86 |
| 42-EB | 85.19 | 11.21 | 96.40 | 0.0 | 1.72 | 0.15 | 0.90 | 0.0 | 2.77 | 0.36 | 0.59 | 2.56 |
| 42-EA | 86.37 | 9.17 | 95.53 | 0.0 | 3.00 | 0.04 | 2.68 | 0.0 | 5.73 | 0.0 | 0.62 | 3.16 |



42-EB and 42-EA are undifferentiated Elmwood samples and are not precisely located.

* It is here emphasized that the species and frequently the total clay are questionable pending further research. Where the total normative analysis is appreciably different than 100% the major error is usually in the clay content. If the theoretical insoluble residue is about the same as quartz and clay and minor constituents, the total clay is nearly correct.

** Largely Ankerite.

Table A-3

X-ray Clay-Mica Analysis

| Sample | Å Group Represented 7Å | 10Å | 14Å | Using 14Å Peak as Unity Relative Intensities 7/14 | 10/14 | Remarks |
|---|---|---|---|---|---|---|
| 37B | T* | X* | T | --- | --- | 10Å 2.5 mm high |
| 42 | T | X | X | --- | 3.3 | 10Å 2.4 mm high |
| 50 | X | X | X | 1.3 | 3.2 | Good Peaks |
| 42-PB | --- | --- | --- | --- | --- | Low in clay |
| 42-J-O | | | | | | |
| J-V | | | | | | |
| EB-1 | X | X | X | 0.9 | 1.5 | |
| EA-1 | X | X | X | 0.8 | 1.2 | |
| 35-J-1 | T | T | T | --- | --- | Low in clay |
| 42-J-1 | --- | T | T | --- | --- | Poor slide |
| 35-1 | --- | --- | --- | --- | --- | Low in clay |
| 34-J | X | --- | X | 1.5 | --- | |
| 26-J | --- | --- | --- | --- | --- | |
| 24-J | --- | --- | --- | --- | --- | |
| 42-CR | X | T | X | 0.7 | --- | |
| OL-1-1 | X | X | X | 1.0 | 1.6 | |
| CR | --- | --- | --- | --- | --- | Poor slide |
| 35-CR | --- | X | X | --- | 1.1 | |
| 34-3 | --- | T | T | | | |
| 26-CR | --- | X | X | --- | 1.8 | |
| 24-CR | X | --- | --- | | | 7Å 1.2 mm |
| 42-ECX | --- | --- | --- | --- | --- | Poor slide |
| 42-ECY | X | --- | T | | | 7Å 2.5 mm high |
| R-1-1 | X | X | X | 0.6 | 1.6 | |
| 26-EC | --- | --- | --- | --- | --- | Background high |
| 24-EC | X | X | X | 0.7 | 1.8 | |
| 34-EB | --- | T | T | --- | --- | |
| E-2 | X | X | X | 0.75 | 1.0 | Poor Peaks |
| 24-EB | X | X | X | 1.1 | 1.0 | Poor Peaks |
| 34-EA | --- | --- | X | --- | --- | 7.5Å Peak |
| 26-EA | --- | T | X | --- | --- | 14Å Very Strong |
| 24-EA | --- | T | --- | --- | --- | Low in Clay |
| OL-2 | X | X | X | 2.0 | 2.0 | 7Å Very Strong |
| 34-1 | X | T | T | --- | --- | |
| 24-OL | --- | T | T | --- | --- | Poor Slide |
| OZ | --- | T | T | --- | --- | Low in Clay |
| R-2 | --- | X | X | --- | 1.3 | |
| 26-OL | --- | X | X | --- | 0.8 | |
| OD | X | X | X | 1.2 | 1.0 | Good Peaks |
| RA | X | X | X | 1.3 | 1.5 | Good Peaks |
| RB | --- | T | T | --- | --- | Insufficiant Clay |

Table A-3

X-ray Clay-Mica Analysis
(2)

| Sample | Å Group Represented | | | Using 14Å Peak as Unity Relative Intensities | | Remarks |
|---|---|---|---|---|---|---|
| | 7Å | 10Å | 14Å | 7/14 | 10/14 | |
| K-3-b | --- | X | X | --- | 1.1 | |
| K-2 | --- | X | T | --- | --- | 10Å = 0.4 mm |
| K-3-a | --- | X | X | --- | 1.0 | |
| 1b | T | T | T | --- | --- | Insufficient clay |
| 6c | | | | | | 10Å 1.5 mm |
| 6c-1 | | | | | | |
| 6c-2 | | | | | | |
| 7b | T | T | T | --- | --- | Feldspar Peak |
| 8c | --- | X | T | --- | --- | 10Å 1.3 mm |
| 8b | --- | --- | --- | --- | --- | Poor Slide |
| 8a | --- | X | X | --- | 0.75 | 14 0.6 mm |
| 1a | --- | X | --- | --- | --- | 10Å 1.8 mm |
| 2e | X | X | --- | --- | --- | 7/10 0.9 |
| 2du | --- | X | --- | --- | --- | 10Å 1.8 mm |
| 2dl | --- | X | --- | --- | --- | 10Å 1.6 mm |
| 4c | X | X | X | 2.7 | 1.7 | |
| 6b | --- | X | X | --- | 2.1 | High Background |
| 6a | | | | | | |
| 7a | X | X | T | --- | --- | 10Å 2.1 mm 7/10 =0.4 |
| 9 | --- | --- | --- | --- | --- | Background high |
| 2c | --- | T | --- | --- | --- | 10Å 2.7 mm high |
| C-1-1 | --- | X | X | --- | 2.0 | |
| P-B-1 | | | | | | |
| 2c-reef | --- | X | X | --- | 1.0 | |
| 2b | --- | X | X | --- | 2.3 | |
| 3b | T | T | T | --- | --- | High Background |
| 4b | X | X | X | 2.5 | 2.0 | |
| 5b | T | X | T | --- | --- | 10Å 1.5 mm |
| 2a | X | X | X | 1.3 | 2.0 | |
| DQ-1-1 | --- | X | X | --- | 1.2 | |
| 4 a | --- | X | --- | | | 10Å 2.3 mm |
| 5a | X | X | X | 1.5 | 1.1 | |
| P-B-2 | X | X | X | 1.8 | 2.0 | Good Peaks |
| P-B-1 | X | X | X | 1.8 | 1.9 | |
| P-A-2 | X | X | T | --- | --- | 7/10 = 0/9 |
| P-A-1 | X | X | X | 1.4 | 2.2 | 7/10 = 0.6 |
| P-M-3 | X | X | X | 1.1 | 1.2 | Two slides (avg.) |
| P-M-2 | --- | --- | X | --- | --- | 14Å = 1.1 mm |
| P-M-1 | --- | --- | T | --- | --- | Feldspar peak |
| SLS G | T | X | T | --- | --- | 10Å 1.6 mm |
| 6c | T | X | T | --- | --- | |

* X is a strong peak and T is a weak peak

Table A-4

Dedolomitization Test and pH Changes

| Sample | pH Change | Comments |
|---|---|---|
| P-M-3 | -0.2 | Expansion 1.3% |
| SLS G** | -0.1 | Expansion 1.3% |
| 2b | -0.8 | Murky solution, 3% quartz 12% clay |
| 9 | -0.6 | 52% quartz, 9% clay |
| 8c | -0.6 | Dolomite with minor impurities |
| 6a, 8b | -0.5 | 8b as 8c. 6a, 18% quartz, 10%clay |
| 2a, 8a | -0.4 | 8a as 8c. 2a, 7% quartz, 11%clay. |
| 7a, 7b, CR, JV-1, P-A-2, OL-2 | -0.3 | 7a, 53% quartz, 15% clay, OL-2 is highest pH change in non-dolomitic rock. |
| 6c, 6b, K-2, 34-J, 24-1 | -0.2 | |
| 24-EB-1, 4a | | |
| EA1-JV2, SLS-E, SLS-I, 5a, 2DV | -0.1 | |
| 2e, 3b, 26EA, 26CR1, 26EB | -0.1 | |
| 34EC, 42EA, 42-PB | -0.1 | |

Measurements were made with a pH meter on 1N NaOH solution used for "dedolomitization reaction" test.

Comments:

1. Changes in pH could be run better on standard weight samples on about 1/4" to 3/8" size range. Measurements should be probably be done by titration.

2. 14 of the 15 most reactive are dolomites and many are siliceous.

3. The consistently large pH changes in the Oak Orchard (8a, 8b, 8c, 7b) and the Penfield (6a, 6b, 7a, 9) members of the Lockport formation may be significant and suggests a likelihood of some sort of "alkali reaction" with solutions in portland cement.

*All samples below line expanded less than 0.1%

Table A-5

Specific Gravity, Thermal Expansion and Sonic Velocity

| Sample | Specific Gravity | | | | Coefficient of Thermal expansion X $10^{-6}$ (-100°F to + 160°F) | | | Compressional Wave velocity X $10^4$ ft/sec (1) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Apparent | Bulk oven dry | Bulk Sat. | True pycnom-eter | Mercury Displace-ment | Normal to bedding | Parallel to NS* | Parallel to EW* | Normal to bedding | Parallel to NS* | Parallel to EW* |
| 37B | 2.69 | 2.78 | 2.79 | 2.72 | | | | | — | 1.79 | 1.81 |
| 42 | 2.71 | 2.72 | 2.73 | 2.73 | | | | | 1.87 | 1.82 | 1.94 |
| 50 | 2.73 | 2.69 | 2.71 | 2.73 | | | | | 1.67 | 1.82 | 1.79 |
| 42-JO | 2.71 | 2.70 | 2.71 | 2.72 | | | | | 1.81 | 2.09 | 1.96 |
| 42-PB | 2.71 | 2.69 | 2.70 | 2.71 | | | | | 1.99 | 1.99 | 2.01 |
| J-V | 2.70 | 2.70 | 2.70 | 2.70 | | | | | 2.02 | 2.06 | 2.08 |
| EA-1 | 2.73 | 2.72 | 2.72 | 2.71 | 2.76 | | | | 2.07 | 2.08 | — |
| EB-1** | 2.71 | 2.71 | 2.71 | 2.71 | 2.70 | 3.71 | 3.26 | 3.26 | 2.04 | 2.08 | 2.08 |
| 35-J-1 | 2.73 | 2.69 | 2.70 | 2.70 | 2.74 | | | | — | — | — |
| 42-J-1** | 2.72 | 2.72 | 2.72 | — | 2.77 | | | | 2.04 | 2.09 | 2.08 |
| 35-1** | 2.71 | 2.69 | 2.70 | 2.70 | 2.69 | 3.28 | 2.70 | 2.70 | 2.04 | 2.06 | 2.10 |
| 34-J | 2.71 | 2.70 | 2.70 | 2.71 | | | | | — | 2.03 | 2.06 |
| 26-J | 2.71 | 2.70 | 2.70 | 2.73 | | | | | 1.75 | 1.84 | — |
| 24-J** | 2.72 | 2.68 | 2.69 | 2.72 | 2.70 | 3.85 | 3.70 | 3.05 | 2.01 | 2.00 | 2.05 |
| 42-CR | 2.71 | 2.71 | 2.71 | 2.71 | | | | | 2.18 | 2.05 | 2.02 |
| OL-1-1 | 2.71 | 2.71 | 2.71 | 2.70 | | | | | 2.05 | — | 2.04 |
| CR | 2.70 | 2.71 | 2.70 | 2.70 | | | | | 2.05 | 2.07 | 2.09 |
| 35-CR** | 2.70 | 2.66 | 2.67 | 2.70 | 2.69 | 3.96 | 3.96 | 3.96 | 2.07 | 2.11 | 2.12 |
| 34-3** | 2.70 | 2.69 | 2.69 | 2.70 | 2.72 | 5.14 | 4.64 | 4.64 | 2.02 | 2.00 | 2.04 |
| 26-CR | 2.76 | 2.69 | 2.71 | 2.77 | | | | | 2.08 | 1.94 | 2.03 |
| 24-CR-2 | 2.70 | 2.66 | 2.67 | 2.70 | | | | | — | — | — |
| 24-CR** | 2.72 | 2.69 | 2.70 | 2.69 | 2.66 | 3.87 | 3.64 | 4.12 | 1.98 | 2.09 | 2.06 |
| 42-ECX | 2.72 | 2.71 | 2.71 | 2.73 | | | | | 2.01 | 2.08 | 2.11 |
| 42-ECY | 2.75 | 2.74 | 2.74 | 2.75 | | | | | 2.04 | 2.06 | 2.03 |

Table A-5

Specific Gravity, Thermal Expansion and Sonic Velocity

| Sample | Specific Gravity: Apparent | Bulk oven dry | Bulk Sat. | True pycnometer | Mercury Displacement | Coefficient of Thermal expansion X $10^6$ (-100°F to + 160°F): Normal to bedding | Parallel to NS* | Parallel to EW* | Compressional Wave Velocity X $10^4$ ft/sec (1): Normal to bedding | Parallel to NS* | Parallel to EW* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R-1-1** | 2.79 | 2.72 | 2.74 | 2.78 | 2.66 | 6.89 | 6.89 | 6.89 | 1.63 | — | 1.52 |
| 34-EC | 2.75 | 2.72 | 2.73 | 2.74 | | | | | 1.59 | 1.66 | 1.54 |
| 26-EC | 2.71 | 2.71 | 2.71 | 2.72 | | | | | 2.25 | 1.86 | 1.89 |
| 24-EC** | 2.76 | 2.71 | 2.75 | 2.76 | 2.70 | 5.57 | 4.57 | 4.57 | 1.87 | 2.02 | 2.02 |
| 34-EB | 2.72 | 2.71 | 2.71 | 2.73 | | | | | — | — | — |
| 26-EB | 2.71 | 2.71 | 2.71 | 2.71 | | | | | 2.05 | 1.94 | 2.11 |
| E-2** | 2.71 | 2.71 | 2.71 | 2.72 | 2.70 | 3.37 | 4.06 | 3.90 | 2.02 | — | 2.02 |
| 24-EB | 2.71 | 2.68 | 2.69 | 2.73 | | | | | 2.02 | 2.05 | 2.03 |
| 34-EA | 2.71 | 2.70 | 2.70 | 2.71- | | | | | 2.01 | 2.95 | 2.04 |
| 26-EA | 2.71 | 2.70 | 2.71 | 2.71 | | | | | 2.06 | 1.93 | 2.01 |
| 24-EA | 2.73 | 2.72 | 2.72 | 2.72 | | | | | 2.05 | 2.05 | 2.05 |
| OL-2** | 2.71 | 2.70 | 2.70 | 2.70 | 2.67 | 4.06 | 3.93 | 3.93 | 2.06 | 2.06 | 2.07 |
| 34-1** | 2.71 | 2.70 | 2.71 | 2.72 | 2.70 | 4.00 | 3.54 | 3.54 | 1.94 | 2.03 | 1.96 |
| 24-OL | 2.71 | 2.69 | 2.70 | 2.70 | | | | | 1.86 | 1.92 | — |
| OZ | 2.76 | 2.70 | 2.71 | 2.75 | | | | | 1.92 | 2.02 | 2.01 |
| R2 | 2.74 | 2.73 | 2.73 | 2.74 | 2.71 | 5.00 | 4.64 | 4.64 | 1.93 | 2.08 | 2.09 |
| 26-OL | 2.71- | 2.71 | 2.71 | 2.71 | | | | | 2.06 | 1.99 | 2.01 |
| OD | 2.77 | 2.54 | 2.62 | 2.81 | | | | | 1.52 | 1.54 | 1.59 |
| RA | 2.80 | 2.60 | 2.68 | 2.81 | | | | | 1.38 | — | 1.31 |
| RB | 2.81 | 2.73 | 2.76 | 2.76 | | | | | 1.89 | 1.90 | 2.02 |
| K-3-b | 2.75 | 2.71 | 2.72 | 2.79 | | | | | 1.89 | 1.95 | 1.95 |
| K-2** | 2.77 | 2.76 | 2.76 | 2.75 | 2.76 | 7.71 | 7.92 | 7.43 | 2.11 | 2.02 | 2.03 |
| K-3-a | 2.79 | 2.79 | 2.79 | 2.80 | | | | | 1.82 | 2.00 | 2.11 |
| 1b- | 2.73 | 2.56 | 2.56 | 2.56 | 2.83 | | | | 1.89 | 1.98 | 1.93 |

Table A-5

## Specific Gravity, Thermal Expansion and Sonic Velocity

| Sample | Specific Gravity: Apparent | Specific Gravity: Bulk oven dry | Specific Gravity: Bulk Sat. | Specific Gravity: True pycnometer | Specific Gravity: Mercury Displacement | Coefficient of Thermal expansion X $10^6$ (-100°F to + 160°F): Normal to bedding | Coefficient of Thermal expansion X $10^6$ (-100°F to + 160°F): Parallel to NS* | Coefficient of Thermal expansion X $10^6$ (-100°F to + 160°F): Parallel to EW* | Compressional Wave Velocity X $10^4$ ft/sec (1): Normal to bedding | Compressional Wave Velocity X $10^4$ ft/sec (1): Parallel to NS* | Compressional Wave Velocity X $10^4$ ft/sec (1): Parallel to EW* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6c** | 2.79 | 2.67 | 2.72 | 2.84 | | 7.75 | 7.75 | 7.75 | 1.76 | 1.92 | 1.93 |
| 7b | 2.77 | 2.67 | 2.72 | 2.88 | | | | | 2.10 | 2.10 | — |
| 8c | 2.60 | 2.57 | 2.59 | 2.63 | | | | | 1.50 | 1.69 | 1.67 |
| 8b | 2.80 | 2.71 | 2.74 | 2.84 | | | | | 1.60 | 1.53 | 1.51 |
| 8a | 2.83 | 2.78 | 2.83 | 2.83 | | | | | 1.80 | 1.59 | 1.70 |
| 1a | 2.70 | 2.66 | 2.69 | 2.82 | | | | | 1.82 | 1.79 | 1.83 |
| 2e | 2.76 | 2.71 | 2.73 | 2.74 | | | | | — | 1.71 | 1.82 |
| 2du** | 2.77 | 2.71 | 2.75 | 2.82 | 2.82 | 7.17 | 7.17 | 7.17 | 1.69 | 1.73 | 1.72 |
| 2dl | 2.71 | 2.67 | 2.68 | 2.83 | 2.76 | | | | — | — | — |
| 4c | 2.75 | 2.69 | 2.73 | 2.82 | | | | | 1.57 | 1.46 | 1.59 |
| 6b | 2.77 | 2.71 | 2.76 | 2.84 | 2.73 | | | | 1.61 | 1.58 | 2.18 |
| 6a | 2.72 | 2.70 | 2.71 | 2.79 | | | | | 1.58 | 1.67 | 1.94 |
| 7a | 2.73 | 2.67 | 2.69 | 2.76 | | | | | 1.41 | 1.50 | 1.33 |
| 9** | 2.73 | 2.71 | 2.72 | 2.74 | | | | | 1.26 | 1.40 | 1.26 |
| C-1-1** | 2.84 | 2.74 | 2.78 | 2.84 | 2.69 | 9.07 | 8.07 | 8.07 | 1.68 | 1.74 | 1.77 |
| 2c | 2.78 | 2.46 | 2.54 | 2.54 | 2.72 | | | | — | 1.92 | 1.89 |
| 2c-reef | 2.82 | 2.73 | 2.81 | 2.84 | 2.70 | | | | 1.52 | 1.56 | 1.59 |
| 2b | 2.64 | 2.50 | 2.56 | 2.84 | 2.82 | | | | 1.34 | 1.52 | 1.50 |
| 3b | 2.80 | 2.64 | 2.69 | 2.84 | 2.79 | | | | 1.84 | 1.91 | 1.87 |
| 4b | 2.83 | 2.78 | 2.81 | 2.85 | | | | | 1.56 | 1.92 | 1.91 |
| 5b** | 2.77 | 2.61 | 2.60 | 2.84 | 2.85 | 6.10 | 5.75 | 6.60 | 1.77 | 1.94 | 1.85 |
| DQ-1-1** | 2.85 | 2.83 | 2.84 | 2.87 | 2.79 | 7.86 | 8.14 | 7.73 | 1.89 | 1.86 | 1.83 |
| 2a | 2.78 | 2.58 | 2.63 | 2.83 | 2.78 | | | | 2.00 | 1.95 | 2.00 |
| 4a | | 2.60 | 2.68 | 2.80 | 2.80 | | | | 1.50 | 1.61 | 1.62 |
| 5a** | 2.78 | 2.72 | 2.76 | 2.81 | 2.82 | 7.96 | 6.71 | 7.43 | 1.74 | 1.87 | 1.82 |

Table A-5

Specific Gravity, Thermal Expansion and Sonic Velocity

| | Specific Gravity | | | | | Coefficient of Thermal expansion X $10^{-6}$ (-100°F to + 160°F) | | | Compressional Wave Velocity X $10^4$ ft/sec (1) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | Apparent | Bulk oven dry | Bulk Sat. | True pycnom-eter | Mercury Displace-ment | Normal to bedding | Parallel to NS* | Parallel to EW* | Normal to bedding | Parallel to NS* | Parallel to EW* |
| P-B-2** | 2.74 | 2.69 | 2.71 | 2.78 | 2.68 | 6.07 | 6.57 | 6.39 | 1.87 | 1.78 | 1.92 |
| P-B-1** | 2.73 | 2.71 | 2.72 | 2.71 | 2.68 | 3.57 | 4.03 | 4.64 | 1.99 | 2.03 | 2.08 |
| P-A-2** | 2.73 | 2.66 | 2.72 | 2.71 | 2.68 | 4.68 | 4.68 | 4.85 | 1.97 | 1.94 | 1.95 |
| P-A-1** | 2.76 | 2.66 | 2.72 | 2.76 | 2.67 | 7.07 | 7.60 | 7.60 | — | 1.77 | 1.79 |
| P-M-3 | 2.73 | 2.65 | 2.68 | 2.75 | | | | | 1.70 | 1.78 | 1.83 |
| P-M-2 | 2.72 | 2.69 | 2.70 | 2.75 | | | | | 1.89 | 1.90 | 1.95 |
| P-M-1 | 2.72 | 2.71 | 2.71 | 2.71 | | | | | 2.04 | | 2.04 |



(1) Compressional wave velocities have been measured on specimens at moisture equilibrium with air at room conditions. Current research at Rensselaer suggests that minor moisture in specimens may influence these velocities.

*NS and EW orientation known only for double asterisked (**) samples, left hand column.

Table A-6

## Water Absorption, Porosity and Soundness

| Sample | Formation | Member | % Water Absorption | % Porosity | New York State Department of Public Works Soundness Tests - % Loss | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Freeze Thaw | Sodium Sulfate | Magnesium Sulfate | Deval Abrasion |
| 37B | Onondaga | Nedrow | 0.5 | 1.8 | 9.8* | 0.0 | 4.4 | 4.1 |
| 42 | Onondaga | Nedrow | 0.6 | 0.3 | 27.6* | 0.0 | 8.2 | 5.0 |
| 50 | Onondaga | Nedrow | 0.6 | 0.0 | 7.8* | 0.0 | 1.9 | 4.3 |
| 42-PB | Manlius | Jamesville | 0.4 | 0.4 | 4.5* | 0.0 | 1.2 | 3.9 |
| 42-J-0 | Manlius | Jamesville | 0.1 | 0.1 | 11.4* | 0.0 | 0.6 | 4.9 |
| J-V | Manlius | Jamesville | 0.0 | 0.0 | 3.8* | 0.0 | 0.0 | 4.7 |
| EA-1 | Manlius | Jamesville | 0.3 | 0.4 | 0.2 | 0.5 | 0.0 | 4.3 |
| EB-1 | Manlius | Jamesville | 0.0 | 0.5 | 0.3 | 0.0 | 0.0 | 3.8 |
| 35-J-1 | Manlius | Jamesville | 0.2 | - | 11.7* | 1.0 | 1.9 | 4.3 |
| 42-J-1 | Manlius | Jamesville | 0.0 | 0.0 | 0.7 | 0.0 | 0.0 | 3.0 |
| 35-1 | Manlius | Jamesville | 0.2 | 0.0 | 0.7 | 0.7 | 0.8 | 4.1 |
| 34-J | Manlius | Jamesville | 0.2 | 0.0 | 0.6 | 0.0 | 0.8 | 3.8 |
| 26-J | Manlius | Jamesville | 0.4 | 0.6 | 3.2* | 0.3 | 2.5 | 3.9 |
| 24-J | Manlius | Jamesville | 0.2 | 0.3 | 0.3 | 0.5 | 2.2 | 4.1 |
| 42-CR | Manlius | Clark Res. | 0.0 | 0.0 | 2.1 | 0.0 | 2.6 | 4.8 |
| OL-1-1 | Manlius | Clark Res. | 0.2 | 0.0 | 2.5 | 0.0 | 0.5 | 5.2 |
| CR | Manlius | Clark Res. | 0.0 | 0.0 | 12.4* | 0.6 | 0.9 | 5.2 |
| 35-CR | Manlius | Clark Res. | 0.3 | 0.2 | | | | |
| 34-3 | Manlius | Clark Res. | 0.1 | 0.0 | | | | |
| 26-CR | Manlius | Clark Res. | 1.0 | 0.5 | 76.8* | 0.6 | 5.2 | 3.5 |
| 24-CR-2 | Manlius | Clark Res. | 1.3 | | 9.4* | 0.6 | 1.6 | 4.5 |
| 24-CR | Manlius | Clark Res. | 0.5 | | 2.0 | 0.5 | 0.2 | 5.9* |
| 42-ECX | Manlius | Elmwood C | 0.2 | 0.2 | 4.6* | 0.0 | 0.9 | 5.2 |
| 42-ECY | Manlius | Elmwood C | 0.1 | 0.0 | 0.9 | 3.3 | 2.4 | 3.9 |
| R-1-1 | Manlius | Elmwood C | 0.9 | 4.4 | 34.4* | 0.0 | 1.0 | 3.3 |
| 34-EC | Manlius | Elmwood C | 0.4 | 0.0 | 6,7* | 0.0 | 0.8 | 3.0 |
| 26-EC | Manlius | Elmwood C | 0.0 | 0.4 | 1.8 | 0.0 | 4.1 | 2.8 |
| 24-EC | Manlius | Elmwood C | 0.6 | 0.5 | 53.2* | 13.8* | 22.2* | 4.3 |
| 34-EB | Manlius | Elmwood B | 0.0 | 0.7 | 2.6 | 0.6 | 1.8 | 3.4 |
| 26-EB | Manlius | Elmwood B | 0.1 | 0.0 | 14.6* | 0.0 | 0.8 | 2.7 |
| E-2 | Manlius | Elmwood B | 0.1 | 0.6 | 5.2* | 0.0 | 0.0 | 2.9 |

Table A-6

Water Absorption, Porosity and Soundness
(2)

| Sample | Formation | Member | % Water Absorption | % Porosity | New York State Department of Public Works Soundness Tests - % Loss | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Freeze Thaw | Sodium Sulfate | Magnesium Sulfate | Deval Abrasion |
| 24-EB | Manlius | Elmwood B | 0.3 | 0.8 | 0.5 | 0.0 | 0.3 | 3.3 |
| 34-EA | Manlius | Elmwood A | 0.2 | 0.1 | 6.9* | 3.7 | 4.4 | 5.4 |
| 26-EA | Manlius | Elmwood A | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 3.1 |
| 24-EA | Manlius | Elmwood A | 0.1 | 0.0 | 0.0 | 0.0 | 0.3 | 3.2 |
| OL-2 | Manlius | Olney | 0.2 | | 0.3 | 0.0 | 0.4 | 3.4 |
| 34-1 | Manlius | Olney | 0.2 | 0.2 | 2.1 | 0.3 | 0.7 | 4.3 |
| 24-OL | Manlius | Olney | 0.2 | 0.0 | 4.5* | 0.0 | 0.8 | 4.4 |
| OZ | Manlius | Olney | 0.3 | 2.5 | 36.5* | 1.3 | 3.9 | - |
| R2 | Manlius | Olney | 0.0 | 1.2 | 6.6* | 0.0 | 1.4 | 3.2 |
| 26-OL | Manlius | Olney (?) | 0.0 | 0.3 | 1.2 | 0.0 | 0.8 | 3.0 |
| OD | Manlius | Thacher | 3.3 | 1.6 | 58.0* | 3.7 | 35.8* | - |
| RA | Manlius | Thacher | 2.7 | 0.3 | 80.6* | 5.5* | 36.0* | - |
| RB | Manlius | Thacher | 1.0 | - | 23.4* | 0.8 | 0.9 | - |
| K-3-b | Cobleskill | | 0.7 | 1.4 | 10.2* | 0.0 | 3.0 | 3.4 |
| K-2 | Cobleskill | | 0.4 | - | 6.7* | 0.0 | 0.0 | 3.5 |
| K-3-a | Cobleskill | | 0.1 | 0.4 | 3.6* | 0.0 | 0.3 | 3.0 |
| 1b | Lockport | Oak Orchard | 0.7 | 1.4 | 0.4 | 0.0 | 0.7 | 4.7 |
| 6c | Lockport | Oak Orchard | 0.5 | 1.7 | 0.2 | 0.0 | 0.8 | 2.9 |
| 7b | Lockport | Oak Orchard | 1.8 | 1.4 | 0.3 | 0.0 | 0.0 | 3.6 |
| 8c | Lockport | Oak Orchard | 0.9 | 1.1 | 0.0 | 0.0 | 0.0 | 3.5 |
| 8b | Lockport | Oak Orchard | 0.7 | 1.3 | 0.0 | 0.0 | 0.0 | 3.3 |
| 8a | Lockport | Oak Orchard | 2.7 | 0.8 | 0.0 | 0.0 | 1.5 | 6.9* |
| 1a | Lockport | Eramosa | 1.1 | 0.4 | 30.3* | 4.2 | 18.3* | 4.2 |
| 2e | Lockport | Goat Island | 1.2 | 2.2 | 3.8* | 1.7 | 4.9 | 3.9 |
| 2du | Lockport | Goat Island | 1.7 | 1.7 | 4.5* | 4.3 | 5.3 | 10.6* |
| 2dl | Lockport | Goat Island | 1.6 | 4.3 | 1.5 | 2.6 | 9.7 | 3.7 |
| 4c | Lockport | Goat Island | 1.3 | 1.4 | 7.0* | 6.1* | 3.5 | 5.2 |

Table A-6

Water Absorption, Porosity and Soundness
(3)

| Sample | Formation | Member | % Water Absorption | % Porosity | New York State Department of Public Works Soundness Tests - % Loss | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Freeze Thaw | Sodium Sulfate | Magnesium Sulfate | Deval Abrasion |
| 6b | Lockport | Penfield | 1.3 | 1.0 | 0.9 | 0.0 | 0.8 | 6.2* |
| 6a | Lockport | Penfield | 0.9 | 2.5 | 0.0 | 1.5 | 3.1 | 3.2 |
| 7a | Lockport | Penfield | 1.5 | 4.5 | 0.3 | 0.0 | 0.0 | 2.5 |
| 9 | Lockport | Penfield | 0.9 | 2.2 | 0.0 | 1.3 | 2.3 | 4.3 |
| C-1-1 | Lockport | Gasport | 1.4 | 5.2 | 38.6* | 1.8 | 27.0* | 4.1 |
| 2c | Lockport | Gasport | 1.4 | 1.7 | 44.2* | 3.9 | 34.8* | 4.6 |
| 2c-reef | Lockport | Gasport | 3.2 | 3.8 | - Insufficient Sample - | | | |
| 2b | Lockport | Gasport | 0.4 | 2.7 | 0.1 | 0.1 | 0.4 | 4.8 |
| 3b | Lockport | Gasport | 1.2 | 1.3 | 0.0 | 0.0 | 0.3 | 5.8* |
| 4b | Lockport | Gasport | 0.9 | 0.6 | 1.3 | 0.0 | 0.6 | 4.4 |
| 5b | Lockport | Brockport | 0.5 | 2.2 | 13.8* | 0.4 | 2.3 | 4.7 |
| 2a | Lockport | Decew | 1.2 | 1.8 | 10.6* | 3.5 | 12.5* | 4.1 |
| DQ-1-1 | Lockport | Decew | 0.5 | 2.6 | 0.9 | 2.7 | 0.8 | 2.7 |
| 4a | Lockport | Decew | 1.4 | 1.9 | 19.4* | 10.0* | 11.0* | 4.7 |
| 5a | Lockport | Decew | 1.4 | 1.5 | 14.6* | 2.5 | 7.1 | 4.4 |
| P-B-2 | Pamelia | | 0.4 | 3.6 | 54.4* | 19.8* | 21.1* | 5.8* |
| P-B-1 | Pamelia | | 0.2 | 0.5 | 1.1 | 0.0 | 0.9 | 4.3 |
| P-A-2 | Pamelia | | 0.5 | 1.1 | 10.9* | 4.3 | 5.8 | 4.3 |
| P-A-1 | Pamelia | | 0.9 | 3.3 | 44.7* | 1.6 | 24.1* | 7.0* |
| P-M-3 | Pamelia | | 1.2 | 0.7 | | | | |
| P-M-2 | Pamelia | | 0.3 | 1.1 | 52.4* | 0.0 | 1.3 | 4.2 |
| P-M-1 | Pamelia | | 0.2 | 0.0 | | | | |

* Unsatisfactory for Type B crushed stone.

TABLE A-7

Water Absorption and Soundness, Catskill Graywackes
(All losses in %)

| Sample Number | % Water Absorption | $MgSO_4$ I | $MgSO_4$ II | F-T I | F-T II |
|---|---|---|---|---|---|
| I | 1.46 | 29.9 (434)* | 31.8 (440) | 23.0 (455) | 25.6 (495) |
| II | 1.25 | 8.9 (560) | 5.4 (465) | 4.5 (580) | 3.9 (415) |
| III | 1.15 | 21.9 (420) | 9.7 (565) | 24.4 (475) | 1.5 (540) |
| IV | 1.19 | 3.6 (835) | 6.5 (765) | 0.0 (795) | 4.2 (785) |
| V | 1.96 | 40.6 (740) | 27.8 (775) | 14.3 (740) | 20.4 (760) |
| VI | 0.69 | 0.0 (610) | 0.8 (636) | 4.2 (660) | 2.3 (555) |
| VII | 1.54 | 0.7 (685) | 1.6 (636) | 8.9 (660) | 4.1 (590) |
| VIII | 1.27 | 6.8 (735) | 13.6 (770) | 12.9 (750) | 7.2 (785) |
| IX | 1.96 | 35.3 (610) | 31.4 (860) | 22.4 (660) | 20.4 (860) |

Analyses made by N.Y.S.D.P.W.
* No. in parentheses indicate initial weight of samples in grams.

Miller and Senechal (1962)

| Sample No. | Orientation* | S-Wave $V_t \times 10^4$ | P-Wave $V_p \times 10^4$ | Poisson's Ratio |
|---|---|---|---|---|
| 5a | $\underline{1}$ | 9.89 | 1.75 | 0.26 |
| | $11_1$ | 10.57 | 1.88 | 0.27 |
| | $11_2$ | 10.50 | 1.87 | 0.27 |
| 34EC | $\underline{1}$ | 9.10 | 1.60 | 0.26 |
| | $11_1$ | 9.05 | 1.66 | 0.29 |
| | $11_2$ | 8.86 | 1.55 | 0.26 |
| 35CR | $\underline{1}$ | 10.28 | 2.08 | 0.34 |
| | $11_1$ | 10.28 | 2.12 | 0.35 |
| | $11_2$ | 10.08 | 2.13 | 0.36 |
| 42ECX | $\underline{1}$ | 10.38 | 2.03 | 0.32 |
| | $11_1$ | 10.40 | 2.08 | 0.33 |
| | $11_2$ | 10.48 | 2.12 | 0.34 |
| 42ECY | $\underline{1}$ | 10.11 | 2.05 | 0.34 |
| | $11_1$ | 10.43 | 2.06 | 0.33 |
| | $11_2$ | 10.43 | 2.03 | 0.32 |
| C-1-1 | $\underline{1}$ | 9.56 | 1.63 | 0.24 |
| | $11_1$ | 9.79 | 1.69 | 0.25 |
| | $11_2$ | 9.98 | 1.78 | 0.27 |
| | | 9.50 | 1.74 | 0.29 |
| J-V | $\underline{1}$ | 10.15 | 2.02 | 0.33 |
| | $11_1$ | 10.38 | 2.08 | 0.34 |
| | $11_2$ | 10.41 | 2.07 | 0.33 |
| P-A-1 | $\underline{1}$ | 9.67 | 1.64 | 0.23 |
| | $11_1$ | 10.28 | 1.78 | 0.25 |
| | $11_2$ | 10.12 | 1.72 | 0.23 |
| | $11_3$ | 10.26 | 1.79 | 0.26 |

*$\underline{1}$ is the orientation perpendicular to the bedding. $11_1$ and $11_2$ are two orientations perpendicular to each other and in the plane of the bedding.

| Sample No. | Orientation | S-Wave $V_t \times 10^4$ | P-Wave $V_p \times 10^4$ | Poisson's Ratio |
|---|---|---|---|---|
| OL-2 | $\perp$ | 10.53 | 2.07 | 0.32 |
| | $\parallel_1$ | 10.48 | 2.07 | 0.33 |
| | $\parallel_2$ | 10.41 | 2.07 | 0.33 |
| C-R | $\perp$ | 10.01 | 2.05 | 0.34 |
| | $\parallel_1$ | 10.33 | 2.08 | 0.34 |
| | $\parallel_2$ | 10.10 | 2.09 | 0.35 |
| EB-1 | $\perp$ | 10.45 | 2.04 | 0.32 |
| | $\parallel_1$ | 10.22 | 2.08 | 0.34 |
| | $\parallel_2$ | 10.28 | 2.09 | 0.34 |
| R-1-1 | $\perp$ | 10.60 | 2.01 | 0.31 |
| | $\parallel_1$ | 9.65 | 1.64 | 0.23 |
| | $\parallel_2$ | 10.23 | 1.90 | 0.30 |
| | $\parallel_3$ | 8.99 | 1.61 | 0.27 |
| K-3-b | $\perp$ | 10.02 | 1.90 | 0.31 |
| | $\parallel_1$ | 10.50 | 1.96 | 0.30 |
| | $\parallel_2$ | 10.37 | 1.96 | 0.30 |
| 2b | $\perp$ | 8.08 | 1.35 | 0.22 |
| | $\parallel_1$ | 8.84 | 1.55 | 0.25 |
| | $\parallel_2$ | 8.88 | 1.51 | 0.24 |
| 2du | $\perp$ | 9.56 | 1.69 | 0.27 |
| | $\parallel_1$ | 10.49 | 1.74 | 0.21 |
| | $\parallel_2$ | 10.35 | 1.73 | 0.22 |
| 4a | $\perp$ | 9.10 | 1.51 | 0.21 |
| | $\parallel_1$ | 11.13 | 1.62 | 0.15 |
| | $\parallel_2$ | 10.63 | 1.62 | 0.13 |
| 7a | $\perp$ | 9.08 | 1.41 | 0.15 |
| | $\parallel_1$ | 9.35 | 1.50 | 0.18 |
| | $\parallel_2$ | 9.98 | 1.33 | 0.14 |
| 8b | $\perp$ | 8.73 | 1.60 | 0.29 |
| | $\parallel_1$ | 9.20 | 1.54 | 0.22 |
| | $\parallel_2$ | 9.49 | 1.52 | 0.18 |

| Sample No. | Orientation | S-Wave $V_t \times 10^4$ | P-Wave $V_p \times 10^4$ | Poisson's Ratio |
|---|---|---|---|---|
| 8c | $\perp$ | 9.05 | 1.51 | 0.22 |
| | $\parallel_1$ | 9.13 | 1.70 | 0.30 |
| | $\parallel_2$ | 8.82 | 1.68 | 0.31 |
| 24Ea | $\perp$ | 10.38 | 2.06 | 0.33 |
| | $\parallel_1$ | 10.38 | 2.05 | 0.33 |
| | $\parallel_2$ | 10.45 | 2.06 | 0.33 |
| 26EB | $\perp$ | 10.29 | 2.06 | 0.33 |
| | $\parallel_1$ | 10.13 | 1.95 | 0.31 |
| | $\parallel_2$ | 10.24 | 2.10 | 0.34 |
| OD | $\perp$ | 8.48 | 1.52 | 0.27 |
| | $\parallel_1$ | 8.38 | 1.54 | 0.29 |
| | $\parallel_2$ | 8.48 | 1.59 | 0.30 |
| 50 | $\perp$ | 8.66 | 1.67 | 0.37 |
| | $\parallel_1$ | 8.86 | 1.82 | 0.35 |
| | $\parallel_2$ | 9.20 | 1.79 | 0.32 |

# APPENDIX B

# TECHNIQUES

B.1 Mineral Analysis Form

i. Restatement of Analysis, Calculation of Carbonates and Minor Constituents

L.O.I. $140^{\circ}$_____ - 25 = _____ $H_2O^+$ ORGANIC MATTER

$H_2O^-$ _____

$H_2O+$, org._____ - $H_2O^+$ calc._____ = _____% CALCULATED ORGANIC MATTER

$SO_3$_____ ÷ 80.06 = ____A x 172.18 = _____ % GYPSUM

S _____ ÷ 64.12 = ____D x 119.97 = _____% PYRITE

$P_2O_5$____ ÷141.95 = ____B x 310.19 = _____ % APATITE

$Na_2O$____ ÷ 61.98 = ____T x 524.30 = _____% ALBITE

$TiO_2$_____ = _____% RUTILE

$CO_2$_____ ÷ 44.01 = _____

CaO_____ ÷56.08 = _____ - A - 3B = _____ - E = _____ x 100.09 ____ % CALCI

MgO _____ ÷40.32 = ____X -E = ____F* ____E x 184.42 = _____ % DOLOMITE

$K_2O$ _____ ÷ 94.20 = ____H

$Fe_2O_3$____ ÷159.70 = _____ -D/2 = ____G

$Al_2O_3$____ ÷101.96 = _____ -T = ____K

$SiO_2$ _____ ÷ 60.06 = ____W

Subtotal _____

24 X D _____ $O_2$ for $SO_2$

8 X Y _____ $O_2$ for ankerite

_____

Wet total 1

* If F < O, calculate ankerite instead of dolomite:

E - X = _____Y X 215.95 = _____ % FERRODOLOMITE

G - Y/2 = _____G

E - Y = _____ X 184.42 = _____ % DOLOMITE

_____ % ANKERITE

Note: treat G' as G below

ii. Calculation of Clay Minerals and Hematite.

(A) If $3H/2F \geq 1$, calculate MgO as illite, balance of $K_2O$ as sericite.

MgO _____ F ÷ 3 = _____ L X either 2840.46 or J = _____ % ILLITE

$K_2O$ _____ H -2L _____ M X 796.48 = _____ % SERICITE

(1) If 8L - K >O, compute illite and hematite.

8L - K = _____ Q ÷ 8L = _____ X 461.92 = _____ + 2782.72 = _____ J

G - Q = _____ X 159.70 = _____ % HEMATITE

(2) If 8L - K < O, regard illite as 2840.46 and compute montmorillonite.

$Al_2O_3$ _____ K -3M - 7L = _____ + 115.48 V/U = _____ +

$Fe_2O_3$ _____ G -1L = _____ V = 720.44 =

_____ U ÷ 2 = _____ Z × _____ = _____ % Mont.

(B) If $3H/2F < 1$, and G-Δ>O, calculate $K_2O$ as illite, balance of MgO as chlorite.

$K_2O$ _____ H ÷ 2 = _____ N X either 2840.46 or 1 = _____ % ILLITE

MgO _____ F ÷ 4 = _____ -.75 N = _____ P X 557.40 = _____ % CHLORITE

(1) If 8N - K > O, compute illite and hematite.

8N - K = _____ Δ ÷8N = _____ X 461.92 = _____ + 2782.72 = _____ I

G -Δ = _____ X 159.70 = _____ % HEMATITE

(2) If 8N - K < O, regard illite as 2840.46 and compute montmorillonite.

$Al_2O_3$ _____ K - 7N -2P = _____ + 115.48 V/U = _____

$Fe_2O_3$ _____ G - 1N = _____ V = 720.44

_____ U ÷ 2 = _____ R X _____ = _____ % MONT.

(C) If 3H/2F 1 and G - O, compute sericite, Fe-sercite, Mont., and Chlorite

$Fe_2O_3$ _____ G X 854.22 = _____ % Fe-SERCITE

$K_2O$ _____ H - G = _____ $\alpha$ X 796.48 = _____ % SERCITE

MgO _____ F ÷ 4 = _____ $\beta$ X 557.40 = _____ % CHLORITE

$Al_2O_3$ _____ K -2G -3$\alpha$ -2P = ___ ÷2 = _____ $\theta$ X720.44 = _____ % MONTMORILLONITE

iii. Calculation of Free Silica.

$$\frac{W - 6T}{\left\{\begin{array}{l}[A] - 24L - 6M - 8Z \\ [B] - 24N - 2P - 8R \\ [C] - 6G - 6\alpha - 2\beta - 8\theta\end{array}\right\}} = \_\_\_\_ \times 60.06 = \_\_\_\_ \%Che$$

iv. Summary

| minor constituents | | % | proportional parts |
|---|---|---|---|
| GYPSUM | | CALCITE | |
| PYRITE | | DOLOMITE | |
| APATITE | | CLAYS | |
| ALBITE | | total | |
| RUTILE | | | |
| HEMATITE | | Dolomite as % total carbonate = | |

Carbonates

CALCITE

DOLOMITE
ANKERITE

clays

ILLITE
SERICITE
CHLORITE
MONT.

CHERT

Subtotal$_2$

v. Calulation of $H_2O^+$

$$\left.\begin{array}{l} [A] \\ \quad 2A \div 12^{L}_{N} + 2M + 2^{Z}_{P} + 4P \\ [B] \\ [C] \; 2A + 2G + 2\alpha + 2\theta + 4\beta \end{array}\right\} = \frac{\qquad}{\times 18.02}$$

$$=$$

$H_2O^+$, Calc. _____

---

vi. Computation Check.

$$\frac{SO_3 + \ldots\ldots + SiO_2}{\text{Dry total}_1} = \frac{\text{Subtotal}_2 - H_2O^+ \text{ calc.} + 8Y + 24D}{\text{Dry total}_2}$$

---

vii. Wet Total Check

$$\text{Subtotal}_2 + \text{calc. org. matter} + H_2O^- = \frac{\qquad}{\text{Wet total}_2}$$

## B. 2 Technique for Clay Mineral Separations and Slide Preparation

Each sample was crushed with a jaw-crusher and sieved. About 500 gms of the sample retained on sieve #18 was put in a 1000 ml beaker. A 3 normal HCl solution was added in sufficient amounts to dissolve 10% of the "free" carbonate (approx. 120 ml of acid). Free carbonate available is estimated by subtracting proportionately the percent of the insoluble matter from the total weight of the sample. The pH of the resulting solution was measured using pH indicators and was invariably between 6.8 and 7.0. The content of the beaker was placed in a porcelain pan and some distilled water added. Occasional shaking and washing is necessary to remove adhering clay from the rock chips. Finally the supernatent liquid is placed back in the 1000 ml beaker and diluted to 800 ml. After mixing with an electric stirrer for 15 minutes, the liquid is ready for sedimentation.

A glass slide (1.8" X 1.0") held by a 5" test-tube holder is suspended in the solution by a horizontal glass rod resting on the top of the beaker. It is removed very carefully after 12 hours and allowed to dry under cover. This method is believed to obtain a slide in which the clay is oriented with the basal section parallel to the glass slide. A General Electric XRD-5s X-ray Diffractometer is used to obtain the diffraction patterns.

B. 3 Ruska Permeameter Technique*

The Ruska mercury permeameter measures the amount of Hg forced into a sample at arbitrary pressures up to 2000 psi. (136 atm.).

In practice, pressure is applied to the Hg by nitrogen gas under pressure. The pressure of the gas on the Hg is regulated by a needle valve and a set of gauges. With application of the pressure the Hg is forced into a certain volume of connected pore space in the rock. Pressure is then applied directly on the Hg by the piston of a displacement pump micrometer. At a given nitrogen pressure and hence Hg pressure, there is a minimum size of pore which will be filled with Hg.

All samples run were 3/4-inch diameter cores with an average length of 1-inch. The axis of the core was generally parallel to the bedding. The ends of the rock core were ground with #220 Carborundum to remove contaminants and then oven-dried for at least 5 hours at 105° to 110°C.

The percent porosity of the sample (%P) was determined from the volume of Hg forced into the rock at 2,000 psi the total volume of the sample ($V_s$) according to the relation:

where $V_T$ = volume of Hg needed to fill sample chamber with sample in place.

*Explanation from Miller and Senechal (1962)

$V_S$ = volume of empty sample chamber

$V = V_S' - V_T$ = volume of sample

$V_{Hg}$ = volume of Hg forced into sample at approx. 2,000 psi.

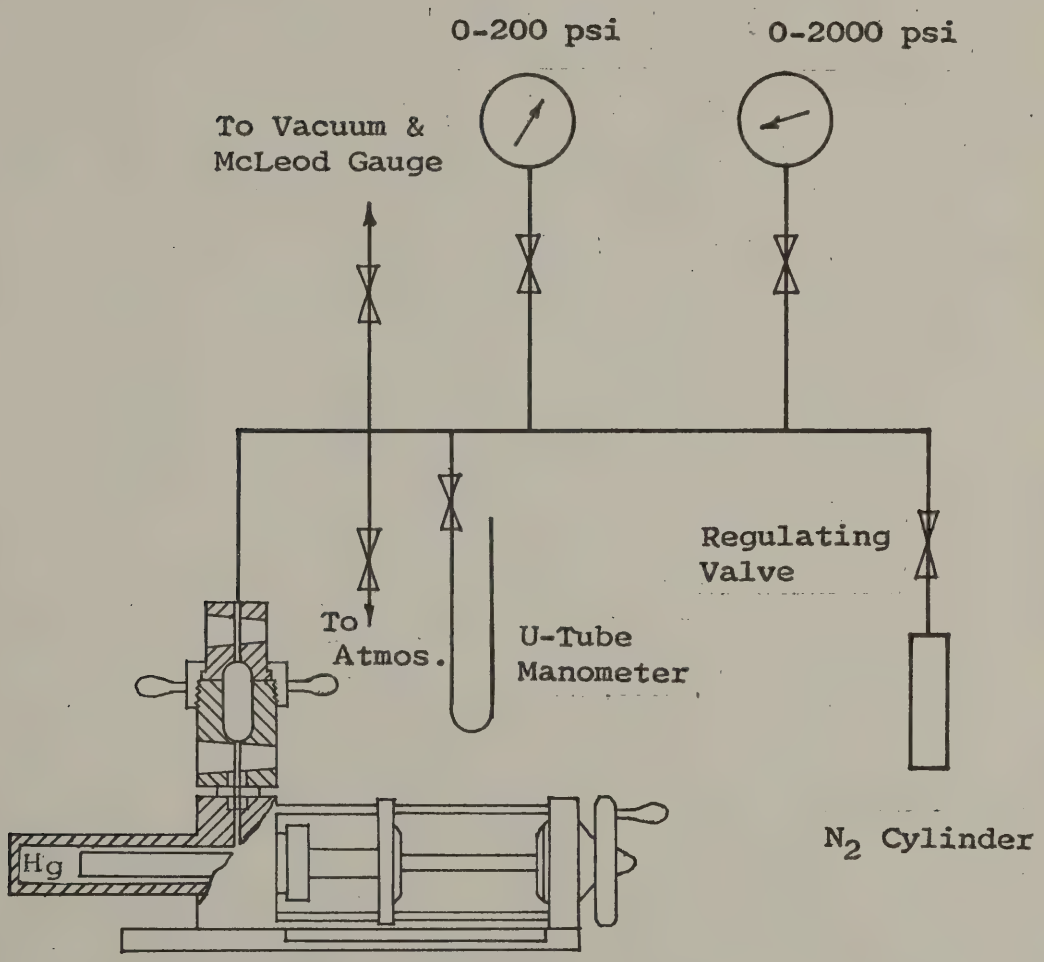
= volume of Hg forced into sample at 2.5 psi.

= compressibility of Hg at 2,000 psi.

$V_T = V_{Hg}$

Figure B-3-1

SCHEMATIC OF RUSKA PERMEAMETER



```
SEQ   STMNT      FORTRAN STATEMENT

      C          NORMATIVE MINERAL ANALYSIS - J.W. KAUFMAN
    1            H2OM=0.21
    2            SO3 =0.05
    3            S   =0.09
    4            A   =0.00062
    5            D   =0.00140
    6            GYP =0.10675
    7            PYR =0.16796
    8       49   0  READ 10,ITEST,XLIG,SIO2,
                 1  AL2O3,FE2O3,TIO2,CAO,XMGO,
                 2   XNA2O,XK2O,H2OP,XINS
    9       10      FORMAT (I5,11F6.2)
   10            APA  = 0.0
   11            ALB  = 0.0
   12            RUT= TIO2
   13            HEM  = 0.0
   14            CAL  = 0.0
   15            DOL  = 0.0
   16            ANK  = 0.0
   17            XILL  = 0.0
   18            SER  = 0.0
   19            CHLO  = 0.0
   20            XMONT= 0.0
   21            CHERT= 0.0
   22            FESER= 0.0
   23            Y   = 0.0
   24            P2O5 = 0.0493* AL2O3
   25            AL2OC= AL2O3 - P2O5
   26            CO2  = XLIG - H2OM
   27            B = P2O5 / 141.95
   28            APA = B * 310.19
   29            T = XNA2O / 61.98
   30            ALB = T * 524.30
   31         0   E =  -CAO/56.08 +A+3.*B
              1   + CO2/44.01
   32            IF (E) 14,12,12
   33       14      E=0.0
   34       12   0  CAL=(CO2/44.01-2.*E)
              1   *100.09
   35            X= XMGO/40.32
   36            F= X-E
   37            G= FE2O3/159.70 - D/2.
```

```
   SEQ    STMNT       FORTRAN STATEMENT

    38                 IF (F)  11,13,13
    39         11      Y =E-X
    40               0  ANK = Y*215.95 +((E-Y)*
                     1       184.42)
    41                  G = G- Y/2.
    42                 GO TO 15
    43         13      DOL = E *184.42
    44         15       H= XK2O/94.20
    45                  XK = AL2OC/101.96-T
    46                  W = SIO2/60.06
    47               0   SUB1 = H2OM +H2OP+SO3 +S
                     1 +P2O5 +XNA2O +TIO2 +CO2 +
                     2  CAO +XMGO +XK2O +FE2O3 +
                     3 AL2OC +SIO2
    48                  WET1 = SUB1-24. *D -8.*Y
    49                 XL=F/3.
    50                 XM = H-2.*XL
    51                 IF(G) 60,61,61
    52         60       G=0.0
    53         61      IF(XK)62,63,63
    54         62       XK=0.0
    55         63      IF(XL)64,65,65
    56         64       XL=0.0
    57         65      IF(XM) 66,67,67
    58         66       XM=0.0
    59         67      Q =8.*XL-XK
    60                 V = G-XL
    61                 U = V+XK-3.*XM - 7.*XL
    62                 Z = U/2.
    63                 IF (V)69,72,72
    64         69       V=0.0
    65         72      IF (Z)73,74,74
    66         73       Z=0.0
    67         74      IF((3.*H)/(2.*F)-1.)24,16,16
    68         16    0 XJ=(Q/(8.*XL))*461.92+
                     1  2782.72
    69                 IF (8.*XL-XK)21,21,17
    70         17      IF (XJ)  18,18,19
    71         18       XILL =XL* 2840.46
    72                  GO TO 20
    73         19       XILL= XL*XJ
    74         20       HEM = (G-Q)*159.70
```

```
   SEQ    STMNT      FORTRAN STATEMENT

    75                 GO TO 22
    76        21       XILL = 2840.46*XL
    77                XMONT=Z*(115.48*V/U+720.44)
    78                IF(V)92,92,22
    79        92      XMONT = 0.0
    80        22       SER = XM * 796.48
    81                 GO TO 40
    82        24       XN= H/2.
    83                DELTA = 8.*XN-XK
    84              0 XI=(DELTA/(8.*XN))*
              190   1 461.92+2782.72
    85                P =  F/4.- 0.75*XN
    86                R = (G-8.*XN+XK -2.*P)/2.
    87                IF(P)75,76,76
    88        75       P=0.0
    89        76      IF(R)77,78,78
    90        77       R=0.0
    91        78      IF(G-DELTA) 33,33,25
    92        32      IF (XI) 26,26,27
    93        26       XILL = XN*(2840.46)
    94                GO TO 28
    95        27       XILL = XN * XI
    96        28       CHLO =P* 557.40
    97                GO TO 41
    98        25       IF ( 8.*XN -XK) 30,30,29
    99        29       HEM = (G-DELTA)*159.70
   100                 GO TO 32
   101        30    0 XMONT =R*(( 115.48*(G-XN))/(G
                    1  +XK-8.*XN-2.*P)+720.44)
   102                IF(G-XN)79,26,26
   103        79       XMONT =0.0
   104                 GO TO 26
   105        33       ALPHA  = H-G
   106                 BETA   = F/4.
   107                IF(ALPHA)80,81,81
   108        80       ALPHA =0.0
   109        81      IF(BETA) 82,83,83
   110        82       BETA =0.0
   111        83    0 THETA =(XK-2.*G-3.*ALPHA
                    1  -2.*P)/2.
   112                IF(THETA)84,85,85
   113        84       THETA =0.0
```

```
SEQ    STMNT      FORTRAN STATEMENT

114      85       FESER = G* 854.22
115                SER    =ALPHA * 796.48
116                CHLO   =BETA* 557.40
117                XMONT  =THETA * 720.44
118               GO TO 42
119      40    0  CHERT =(W-6.*T-24.*XL-6.*
                 1  XM-8.*Z)*60.06
120               GO TO 44
121      41    0  CHERT = (W-6.*T-24.*XN-2.*P
                 1  -8.*R)*60.06
122               GO TO 45
123      42    0  CHERT =(W-6.*T-6.*ALPHA
                 1  -2.*BETA-8.*THETA)*60.06
124               GO TO  46
125      44    0  H2OC = (2.*A+ 12.*XL+2.*XM
                 1   +2.*Z +4.*P)*18.02
126               GO TO 47
127      45    0  H2OC= (2.*A+12.*XN+2.*XM+2.
                 1    *R +4.*P)* 18.02
128               GO TO 47
129      46    0  H2OC = (2.*A+2.*G +2.*ALPHA
                 1   +2.*THETA +4.*BETA)* 18.02
130      47       IF(HEM) 38,91,91
131      38       HEM =0.0
132      91       IF(CHERT)90,39,39
133      90       CHERT = 0.0
134      39    0  SUB2=GYP+PYR+APA+ALB+RUT
                 1  +HEM+CAL+DOL+ANK+XILL
                 2  +SER+CHLO+XMONT+CHERT
                 3  +FESER
135           0  DOLPC = ((DOL+ANK)/(CAL+DOL+
                 1  ANK))*100.
136              DRY1=SUB1-H2OC-H2OM
137              DRY2=SUB2-H2OC+8.*Y+24.*D
138              CORGM = H2OP/H2OC
139              WET2  = SUB2+CORGM +H2OM
140           0  TCLAY =XILL+SER+FESER+CHLO+
                 1  XMONT
141              TCARB =CAL+DOL+ANK
142              TMC = GYP+PYR+APA+ALB+RUT+HEM
143              CCC = TCLAY+CHERT+CORGM+TMC
144              XNMT= TCLAY+CHERT+TMC
```

```
SEQ   STMNT      FORTRAN STATEMENT

145            0  CMT = AL2O3+FE2O3+SIO2+TIO2+
               1   XINS
146            0  PRINT 48,ITEST,XLIG,SIO2,
               1   AL2O3,FE2O3,TIO2,CAO,XMGO,
               2   XNA2O,XK2O,H2OP,XINS,CAL,
               3   DOL,ANK,TCARB,DOLPC,XILL,
               4   SER,CHLO,XMONT,FESER,TCLAY,
               5   CHERT,GYP,PYR,APA,ALB,RUT,
               6   HEM,TMC,CORGM,H2OC,SUB1,
               7   SUB2,WET1,WET2,DRY1,DRY2,
               8   CCC,XNMT,CMT
147      48    0  FORMAT (I8,11F8.2/10F10.3/
               1   10F10.3/10F10.3//)
148               GO TO 49
149               STOP
150               END
```

B. 5 Techniques for Determining Insoluble Residue

In the process of preparing samples from which cores could be cut, an irregularly shaped block was cut to yield a 3 inch cube. Some of the side pieces cut from the block in this operation were reserved for insoluble residue preparation.

These pieces, weighing one hundred grams or more, were broken up into pieces of not over 1 inch cubes using a rock splitter. The broken pieces were fed through a crusher to reduce them to a mixture of dust, powder, chips and flakes. This mixture was shaken on a wire mesh sieve, approximately a W.S. 25. The material was passed through a McCool pulverizer to reduce the chips to a fairly uniform powder.

The powder was collected and one hundred and twenty five grams was placed in a clean beaker which had been carefully weighed and marked.

About an inch of water was added to the bottom of the beaker to reduce the initial violence of the reaction cone of HCl coming in contact with carbonate powder. 50% HCl was slowly added while the mixture was being stirred. Frequent pauses were required to allow the effervescence to subside and when it subsided more acid was added until no additional reaction was noted with the addition of fresh acid.

The mixture was allowed to stand until the insoluble and undissolved material had settled to the bottom of the beaker and the solution was clear. The supernatant liquid was poured off, fresh acid added and the mixture gently warmed over a bunsen burner. The mixture was maintained at nearly boiling temperature for fifteen minutes until all evidence of effervescence had ceased. It was then allowed to cool.

When the insoluble material had settled to the bottom, the liquid was poured off and tap water was added to fill the beaker. The mixture was stirred and again allowed to settle. After several such decantations it was felt that the acid had been effectively removed. The final liquid was poured off carefully to remove as much liquid as possible without loss of sample.

The beakers were then placed in a heating oven maintained at 100°C. When the insoluble material on the bottom of the beaker was completely dry, the beaker was removed from the oven and allowed to cool.

Then the beaker and its contents were weighed and the percentage of insoluble residue computed. The weight of the residue was determined by subtracting the weight of the dry, empty beaker from the weight of the beaker containing the dried, insoluble residue. For 100 grams of initial sample the weight of the residue in grams equals the percentage of residue. For 25 grams of initial sample, the weight of the residue in grams times 4 equals the percentage of residue.

B. 6 Technique for Measuring Dedolomitization

A ½ inch core one to two inches long was cut perpendicular to the bedding of each sample tested. The core was trimmed on a water lubricated carborundum grinding wheel so that the ends tapered to an obtuse angled point. Care was taken in turning the ends to an obtuse angled point. Care was taken in turning the ends to insure that the point was as close to the center line of the core as possible and that the point did not contain any flat spots or ridges.

The cores were placed in polyethylene bottles, one core to a bottle with the sample number recorded on the side of each bottle.

The cores were measured on a Browne and Sharp micrometer with a measuring range from 1 to 2 inches with measurements read to 0.0001 inch. The micrometer was mounted on a wooden block and secured to the block by means of two small posts and a clamp to hold the micrometer stationary. A groove was cut in the block between the measuring faces of the micrometer to accommodate the core and to bring the end points of the core to the center of the measuring faces of the micrometer.

Each time a measurement was made, each sample was removed from its bottle with a pair of tweezers, rinsed in tap water, dried with a soft cloth and measured three times. The movable micrometer face was backed off from contact with the core and the core was rotated 30° to 40° between measurements. Measurements were made with the micrometer

adjusted to a spring loaded force of one ounce. The average of the three measurements was recorded as the measurement for the date.

After the initial measurement the sample bottle was filled with tap water to cover the core. The cores were measured at weekly intervals until they attained a constant length. Small expansion or contraction could be expected to occur during this period which generally covered 3 weeks.

When the sample had attained a constant length, as indicated by a length change of not over 0.1 to 0.2% for one week, the water was poured off and replaced with 1.0 molar NaOH to cover the sample. The sample was again measured at weekly intervals until the significant expansion stopped or the sample had shown no expansion after five (5) weeks. Significant expansion was considered to have ceased when the rate of expansion declined rapidly.

At the conclusion of the test period those samples showing no expansion were discarded, while those showing expansion were put in a labeled jar for storage.

## B. 7 Techniques for Determining Specific Gravity and Water Absorption

A. Water absorption

1. Water absorption studies were performed at RPI in accordance with the provisions of ASTM test C 127-59. Additional water absorptions were measured by Rensselaer personnel at the N.Y.S.D.P.W. materials testing laboratory on the same bulk samples which were submitted to N.Y.S.D.P.W. for soundness testing.

2. At RPI

A large sample of each unit under examination was broken up with a sledge hammer and a rock splitter to provide 10 pieces weighing from 30 to 60 grams each.

The samples were washed under a water tap to remove any remaining chips and powder.

A beaker was weighed using a double pan balance and the weight recorded. The washed samples were placed in the beaker and oven dried in a forced draft drying oven maintained at 105°C. The samples were dried for twenty four (24) hours and then removed, allowed to cool and weighed to yield an oven dry weight in air,

The beaker containing the samples was then filled with water to cover the samples completely and allowed to soak for twenty four hours. The water was then emptied out of the beaker. The samples were blotted to a surface dry condition and the beaker was wiped dry. Then the beaker containing the surface-dry samples was again weighed in air.

The weight of the beaker was subtracted from the beaker plus oven dried sample weight and beaker plus saturated surface dry sample weight to provide the sample weight.

Water absorption was computed as follows:

$$\text{Absorption, per cent} = \frac{B-A}{A} (100)$$ where:

A = weight in grams of oven dry sample in air

B = weight in grams of saturated surface-dry sample in air.

3. At N.Y.S.D.P.W.

Water absorption studies were also performed on all samples submitted to N.Y.S.D.P.W. for soundness testing.

The oven used for drying the samples is a non-forced draft double door oven which has a removable upper rack allowing two levels of samples to be placed inside. The oven is a heating oven maintained at 100°C temperature except from 2:30 to 3:30 PM when samples are placed in the oven.

Two scales were used to measure the sample weights. The first is a Toledo single pan balance with a platform for additional weights. The scale measures up to 500 grams (plus any added weights on the platform) with an accuracy to one (1) gram and interpolation to one half (½) gram.

The second set of scales is a Precision Scientific Company double pan scale with a wire basket immersed in a pail of water, accuracy 0.5 grams. The basket was secured by means of a wire attached to the arm of one pan and passing through a hole drilled on a bench. The basket was secured to the wire by means of a hook so that the basket could be removed. The balance is counter weighted against the weight of the apparatus so that the two pans are in balance.

The sample was removed from the paste-board storage container and put into a metal pan. These were placed in a drying oven at 3 PM and oven dried overnight. At 8:30 the following morning the sample was removed, allowed to cool and the dry weight was determined with the Toledo single pan balance. The sample was then placed in a steel cylinder covered with water and allowed to soak for twenty four (24) hours. The sample was then removed from the water, surface dried with a cloth and the saturated, surface dry weight recorded using the same scales.

The sample was then placed in the wire basket suspended in water from the double pan balance and the saturated weight in water measured and recorded.

In all cases the scales were checked for correct zero reading before and after a series of measurements using several one hundred and fifty gram weights. The saturated weight in water was determined to allow subsequent computation of specific gravity. Water absorption percentages were computed using the previously outlined formula.

B. 8 Techniques for Freeze-Thaw and Sulfate Soundness Tests

A. Magnesium sulphate soundness tests were performed at RPI on small amounts of sample and freeze-thaw tests were performed by the N.Y.S.D.P.W. on 2 inch cubes cut from a large sample block at RPI.

Later magnesium sulphate, sodium sulphate, freeze-thaw and abrasion tests were performed by the N.Y.S.D.P.W. on standard sized bulk samples broken out of large blocks (see sample preparation)

B. Magnesium Sulphate soundness test procedures, R.P.I.

Magnesium sulphate tests were performed on small samples averaging 1 cubic inch from each unit then under investigation.

The solution was prepared using Fisher Scientific Co. reagent grade magnesium sulphate. A large enough amount of this was added to warm (35-40°C), de-ionized water so that the solution would be saturated at this temperature. The solution was then allowed to cool to room temperature ad placed in a flask to await use. The specific gravity varied between 1.295 and 1.305, at room temperature.

For each sample a covered jar and a small beaker were provided. The jar was large enough to contain the sample and allow it to be completely covered by the solution. Both jar and beaker were marked with the sample designation and placed side by side.

The samples were washed in tap water, placed in their beakers and oven dried using a Precision Scientific Company drying oven maintained at 100°C.

After a twenty four hour drying period the samples were removed, allowing to cool and weighed on an analytical balance to nearest 0.001 g.

The sample was then placed in its jar, covered with solution, capped and the time noted. The sample was allowed to soak for eighteen (18) hours. Then each sample was removed from its jar and placed in its corresponding beaker and the beaker placed in the drying oven. The sample was dried for

five hours and was then removed. The sample was allowed to cool for one hour and then returned. The sample was allowed to cool for one hour and then returned to its bottle and solution to complete one cycle.

Ten (10) cycles were run, each of twenty four (24) hours duration after which the samples were washed to remove any sulphate. The sample was considered to be free of sulphate when the wash water showed no $BaSO_4$ precipitate upon the addition of $BaCl_2$.

After the sulphate was removed from the sample, it was oven dried for twenty four (24) hours, reweighed to the nearest 0.001 gm. and the percentage loss computed

C. Procedure for freeze-thaw test, R.P.I. part

Freeze-thaw test samples were cut from the same large block which provided samples for magnesium sulphate soundness test and consisted of two, two inch cubes. These were weighed on a double pan balance with an accuracy of 0.1 gm., and sent to the N.Y.S.D.P.W. materials testing laboratory in Albany for 25 cycle freeze-thaw testing. Upon their return to RPI after completion of freeze-thaw testing the samples were reweighed and the percentage of loss computed.

(The procedures used by the N.Y.S.D.P.W. are not included, but can be obtained from the N.Y.S.D.P.W.).

## B. 9 Some Details of the Technique for Determining Thermal Expansion

### Sample Preparation

Specimens for this test were prepared by cutting ¼" prisms of 1.5" to 2" long in three mutually perpendicular directions along and perpendicular to the bedding plane. The end-face diagonal was in all cases approximately 3/8" long. The sides and the ends were made parallel and the lengths were measured to a precision of ± 0.005".

### Apparatus

The equipment used included a Missimer Refrigerator-oven Testing Chamber for temperature control, a Leeds and Northrop type K2 potentiometer and a recording dilatometer which is sensitive to length changes as small as three millionths of an inch.

### Procedure

For detailed procedure see J. L. Rosenholtz and D. T. Smith, American Mineralogist, vol. 34, pp. 846, 1949.

## B. 10 Technique for Determining Compressional and Shear Wave Velocity

### Preparation of Samples

Cylindrical rock cores (0.75" dia. 1 to 2" length) are cut using a Ruska coring apparatus and the bases lapped parallel to within ± 0.0005". Three cores are usually prepared - one perpendicular to bedding, two parallel to bedding and mutually perpendicular. Silver paint is applied to the bases and along the long diameter of the core to insure electrical contact.

Apparatus

The apparatus consists of a signal generator, a sample holder and a "Tektronix" Type 543 Oscilloscope. For details see Ahrens and Katz (1962).

Procedure

After placing the rock core in the sample holder and electrical contact has been checked, the signal generator is turned on inducing a force on the barium titanate transducer at one end. The transducer induces a wave train with the compressional wave propagated through the rock core at a velocity ($V_p$) given by:

$$V_p = \left(\frac{K + 4/3\,\mu}{\rho}\right)^{1/2}$$

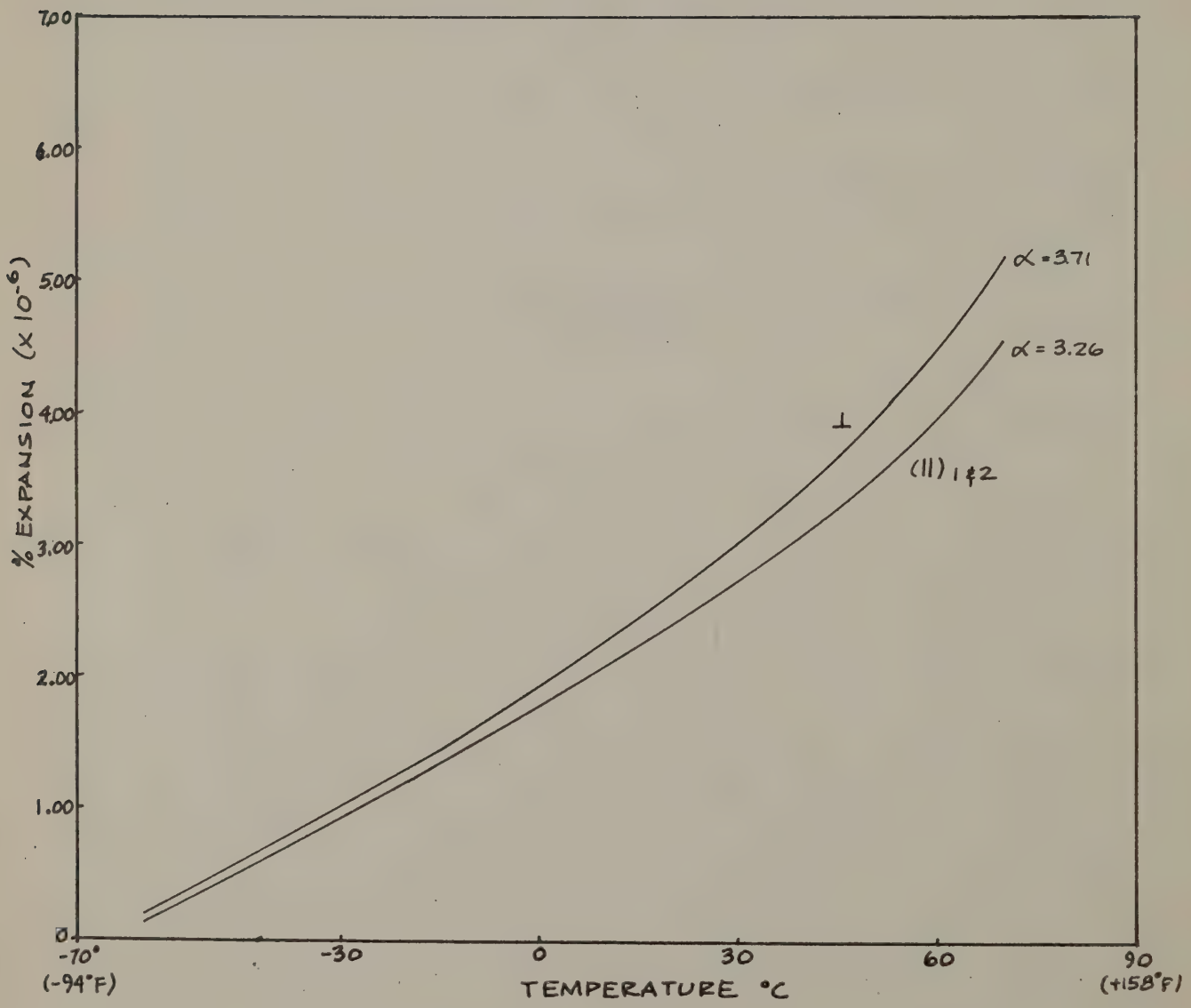
Where K = bulk modulus, $\mu$ = rigidity modulus, $\rho$ = density. At the same instant movement of the first transducer is excited, electrical contact is made with the transducer at the other end of the core. The difference in time between these two arrivals (in milli sec) can be expressed as the sonic velocity if the length of the core is known precisely. Thus, the sonic velocity, in feet/sec., is a measure of the degree of ordering or anisotraphy of the rock core in spite of the extreme variation in individual grain properties.

# APPENDIX C

## THERMAL EXPANSION CURVES

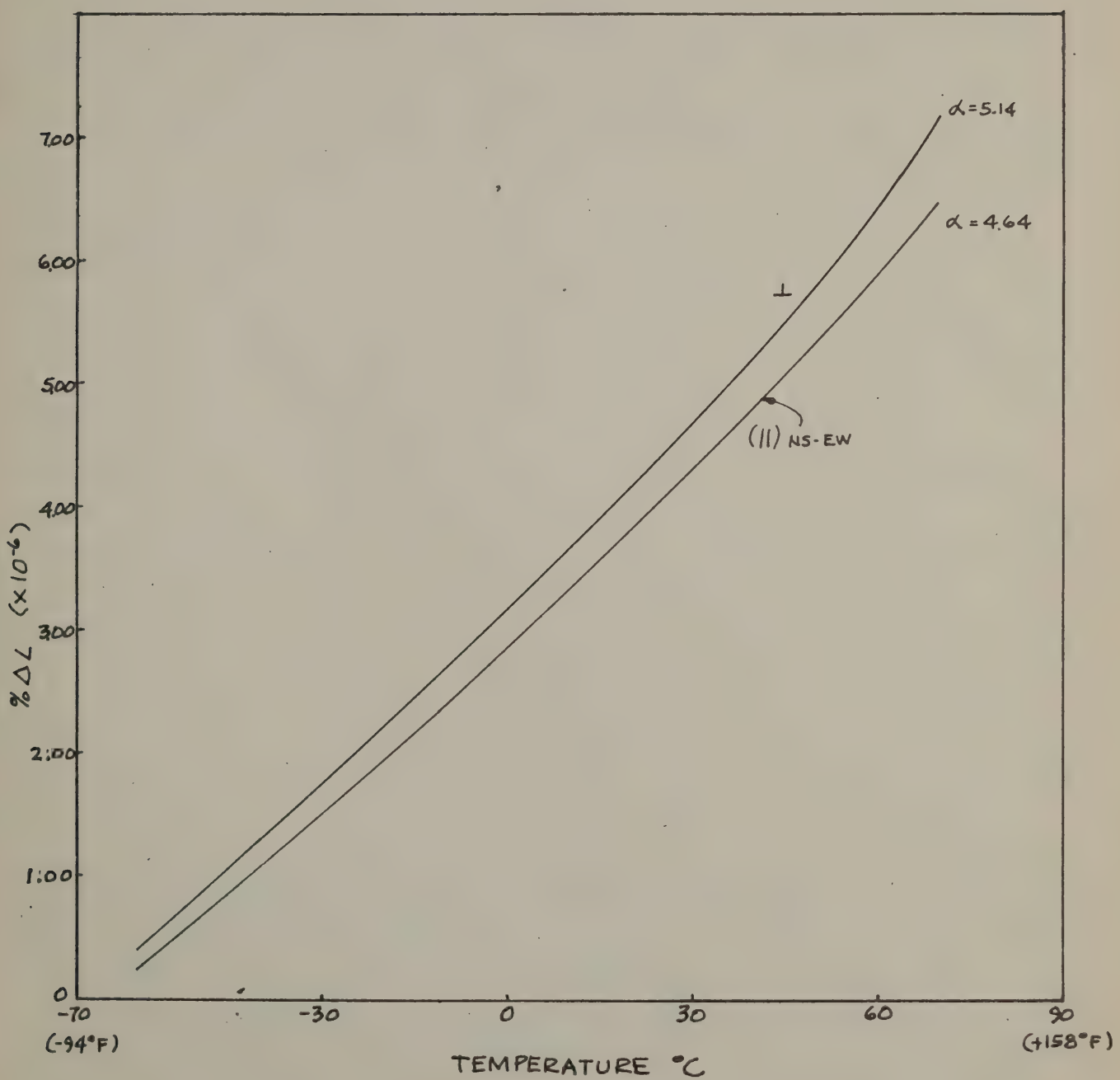
# THERMAL EXPANSION CURVE

## FOR SAMPLE E-B-1

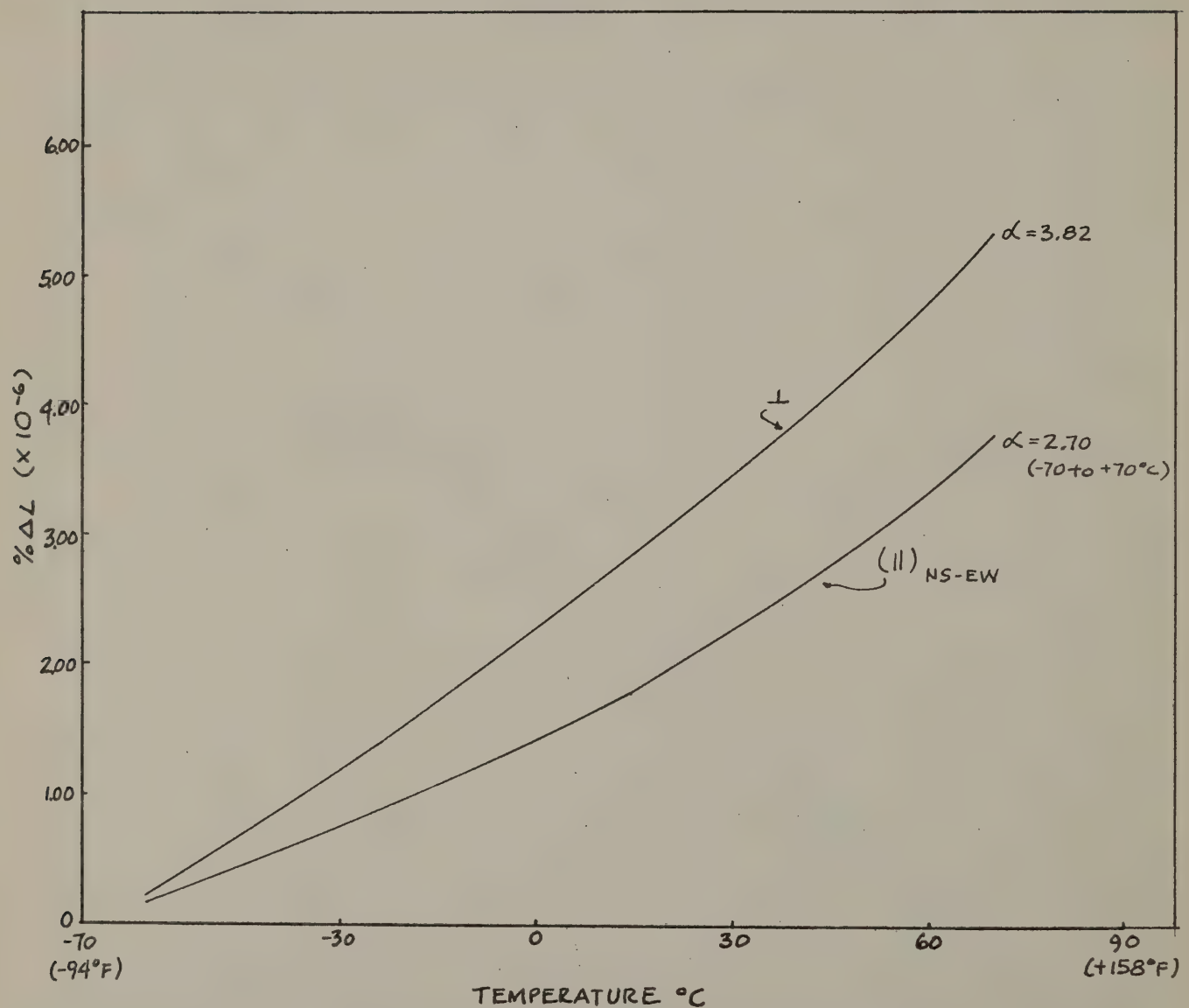


# THERMAL EXPANSION CURVE

## FOR SAMPLE 34-3

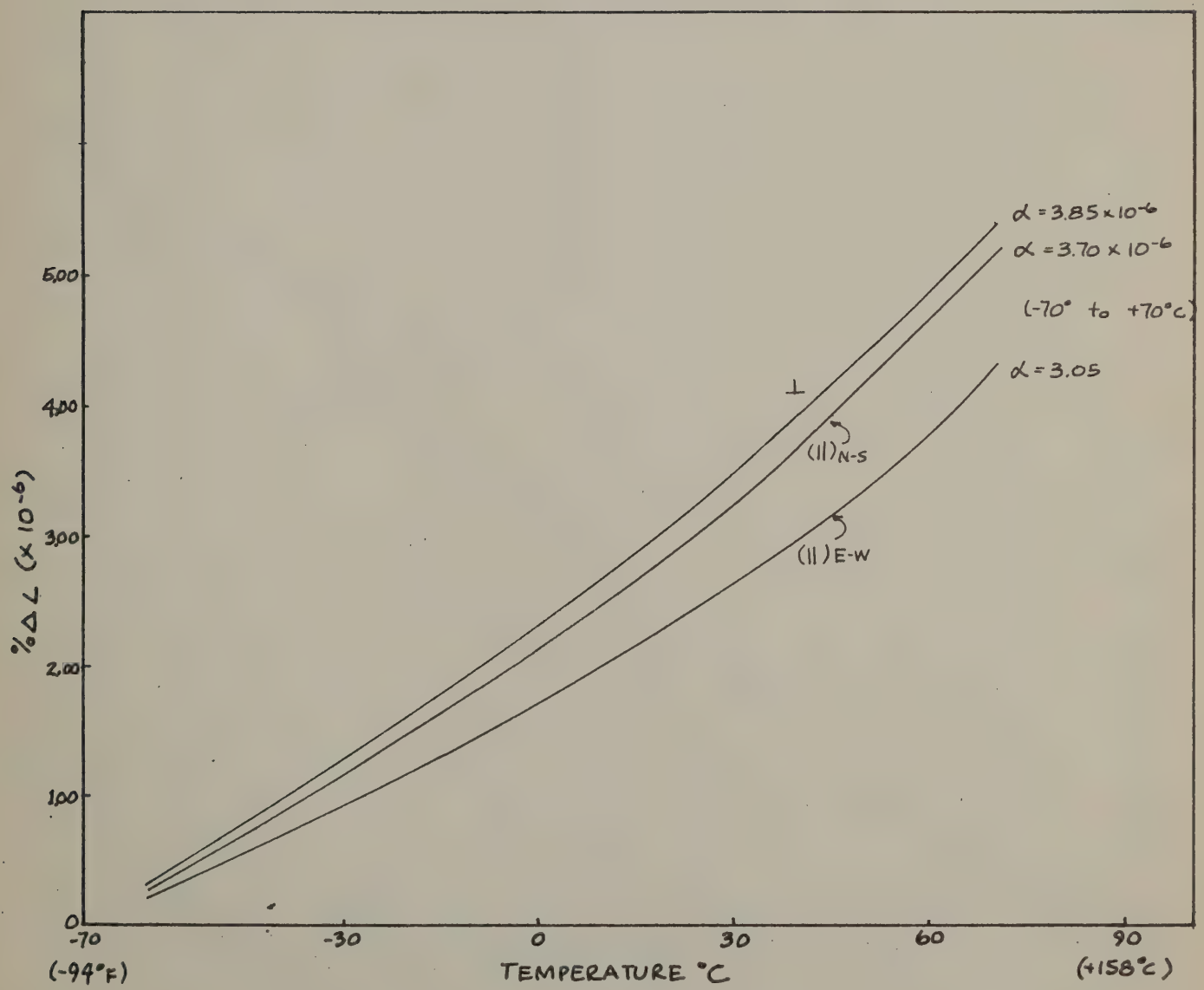


# THERMAL EXPANSION CURVE
## FOR SAMPLE 35-1

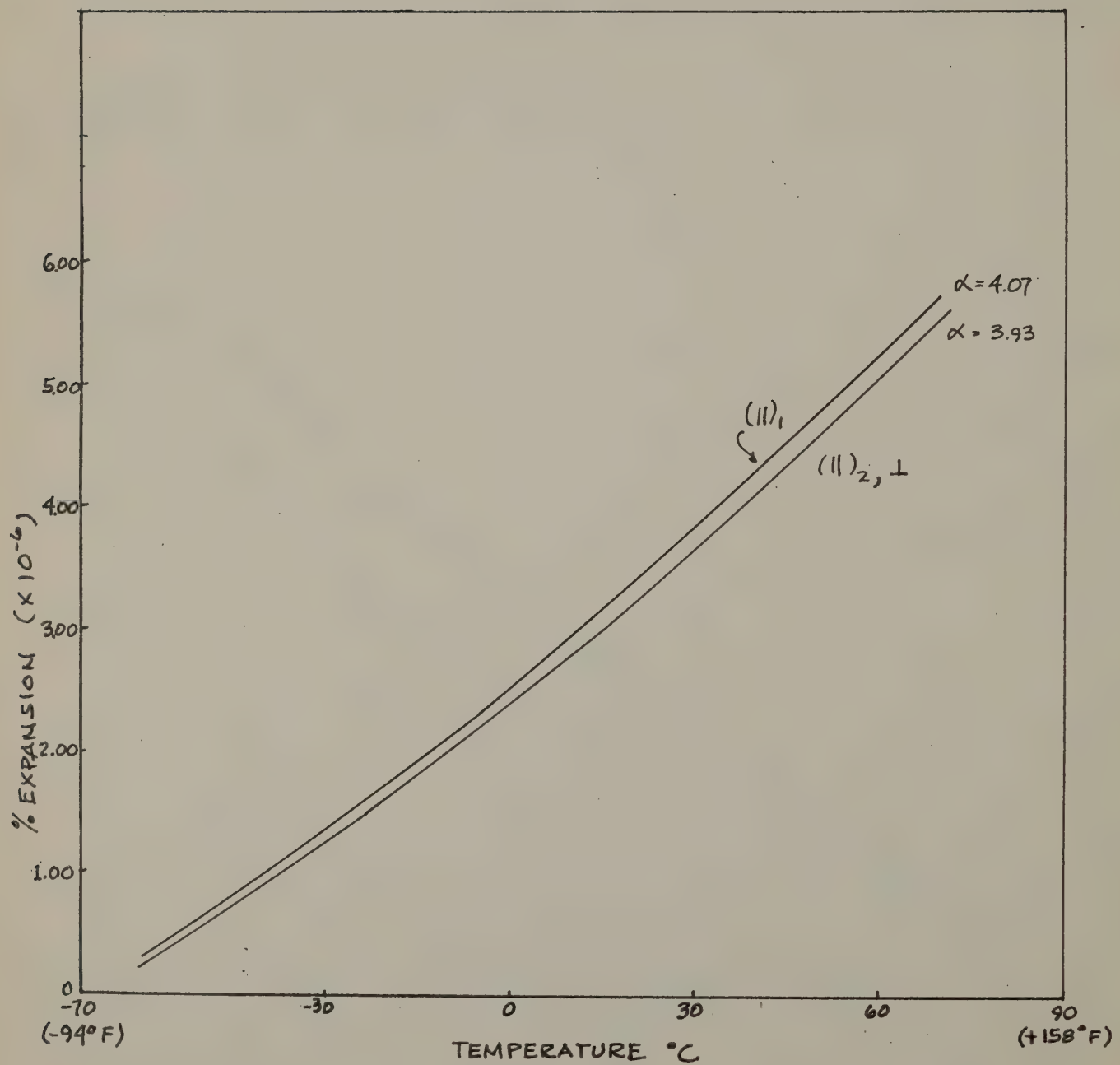


# THERMAL EXPANSION CURVE

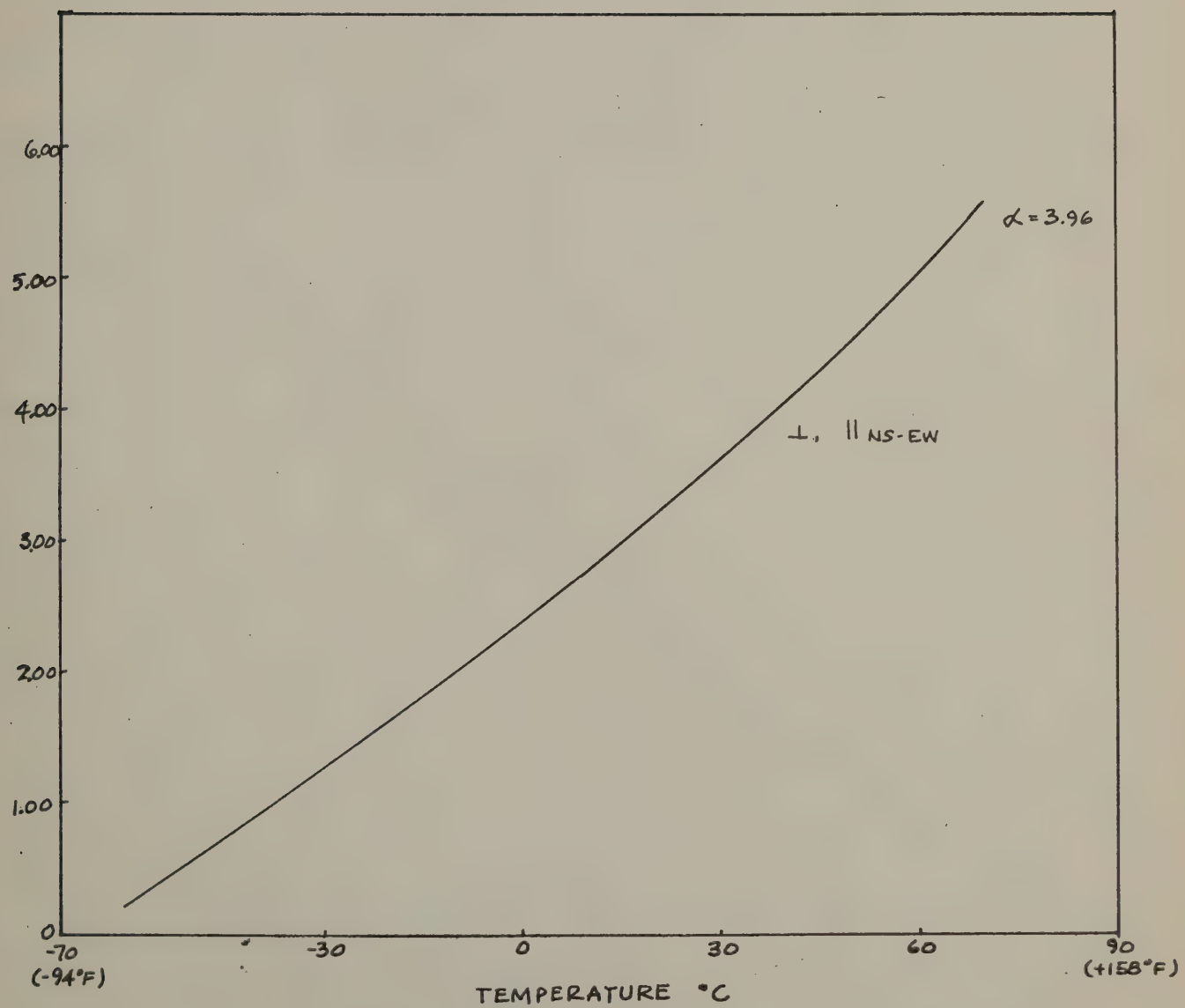
## FOR SAMPLE 24-J-1



# THERMAL EXPANSION CURVE
## FOR SAMPLE OL-1-1

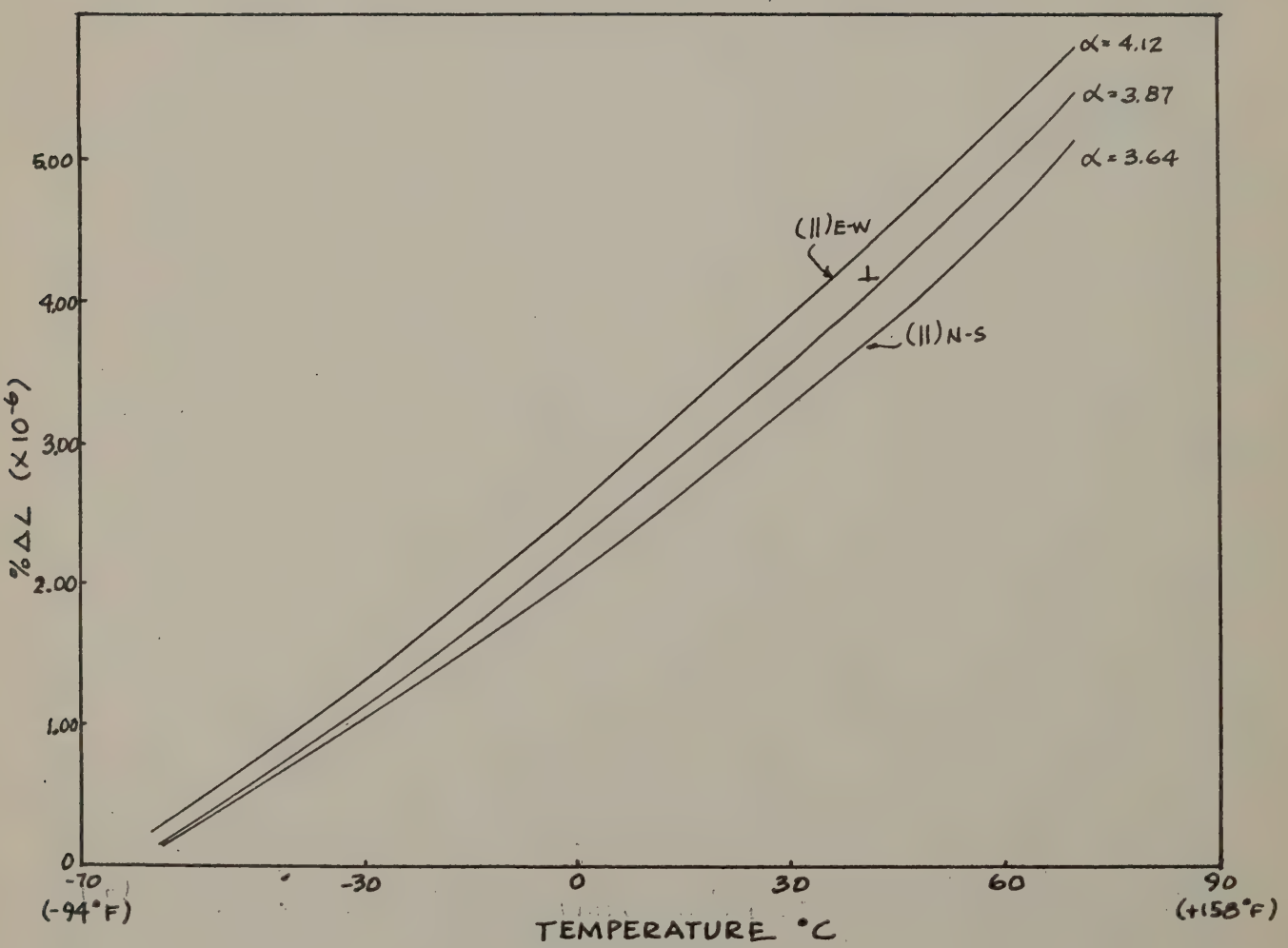


# THERMAL EXPANSION CURVE
## FOR SAMPLE 35-CR

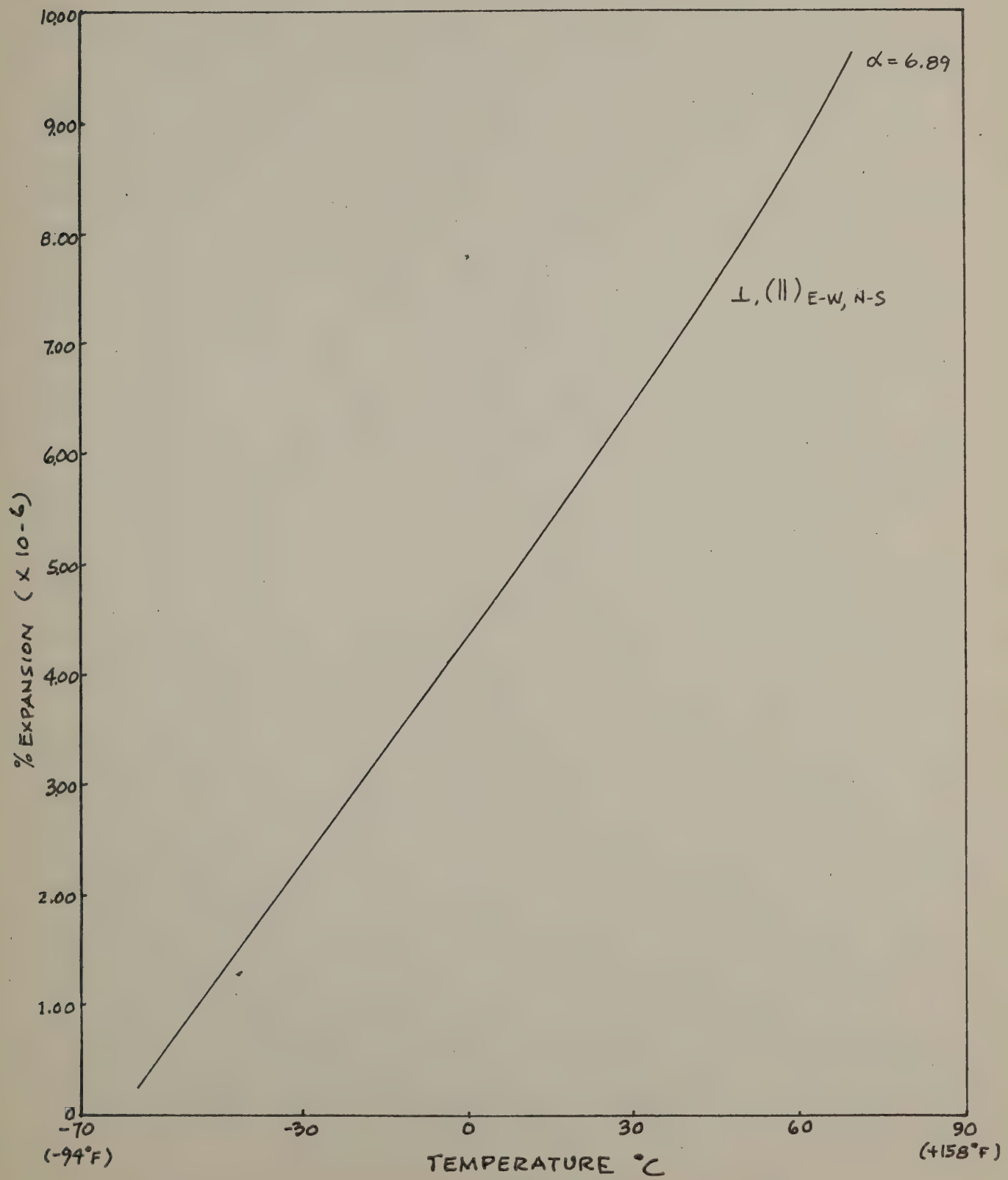


# THERMAL EXPANSION CURVE

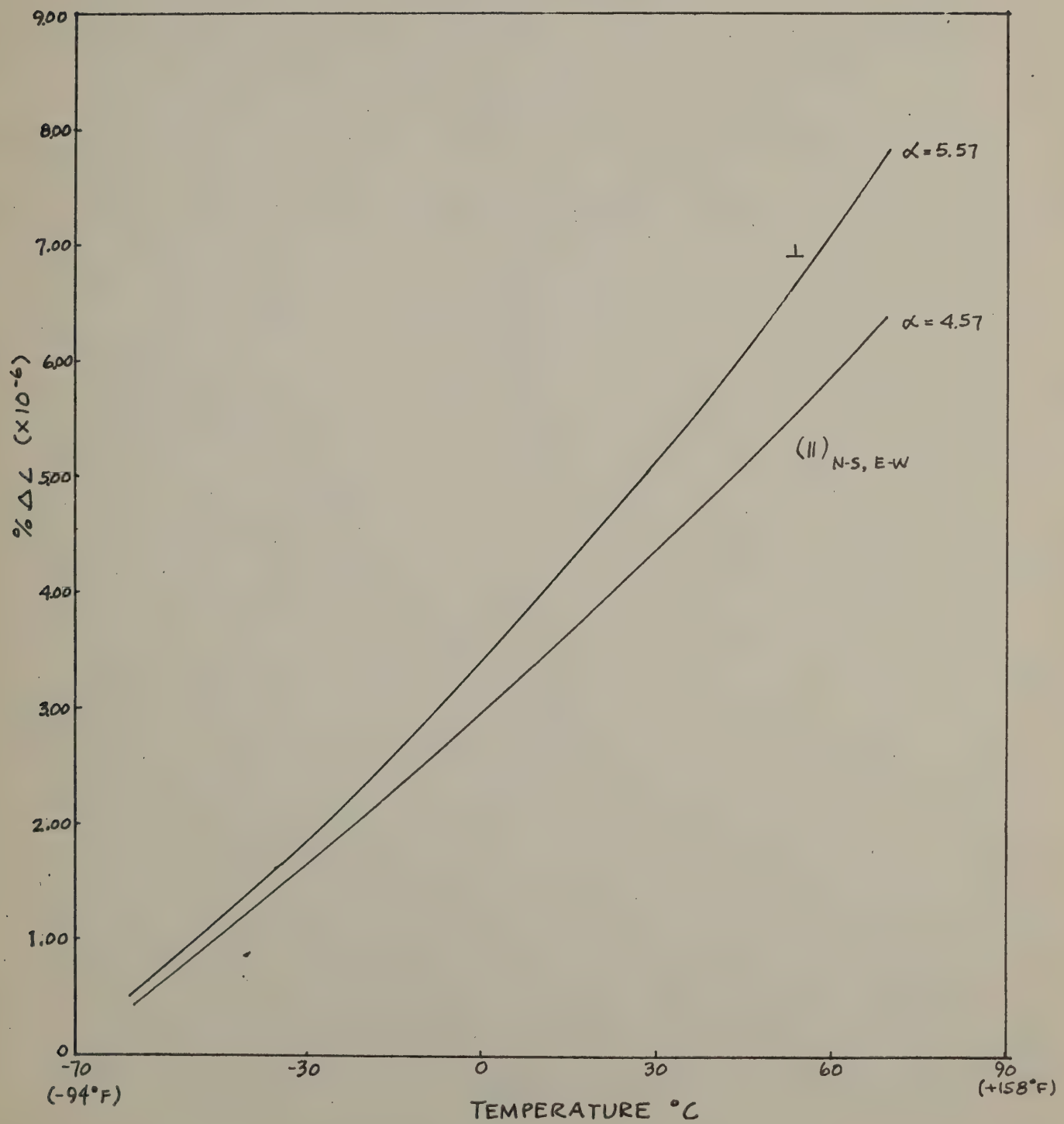
## FOR SAMPLE 24-CR



# THERMAL EXPANSION CURVE
## FOR SAMPLE R-1-1

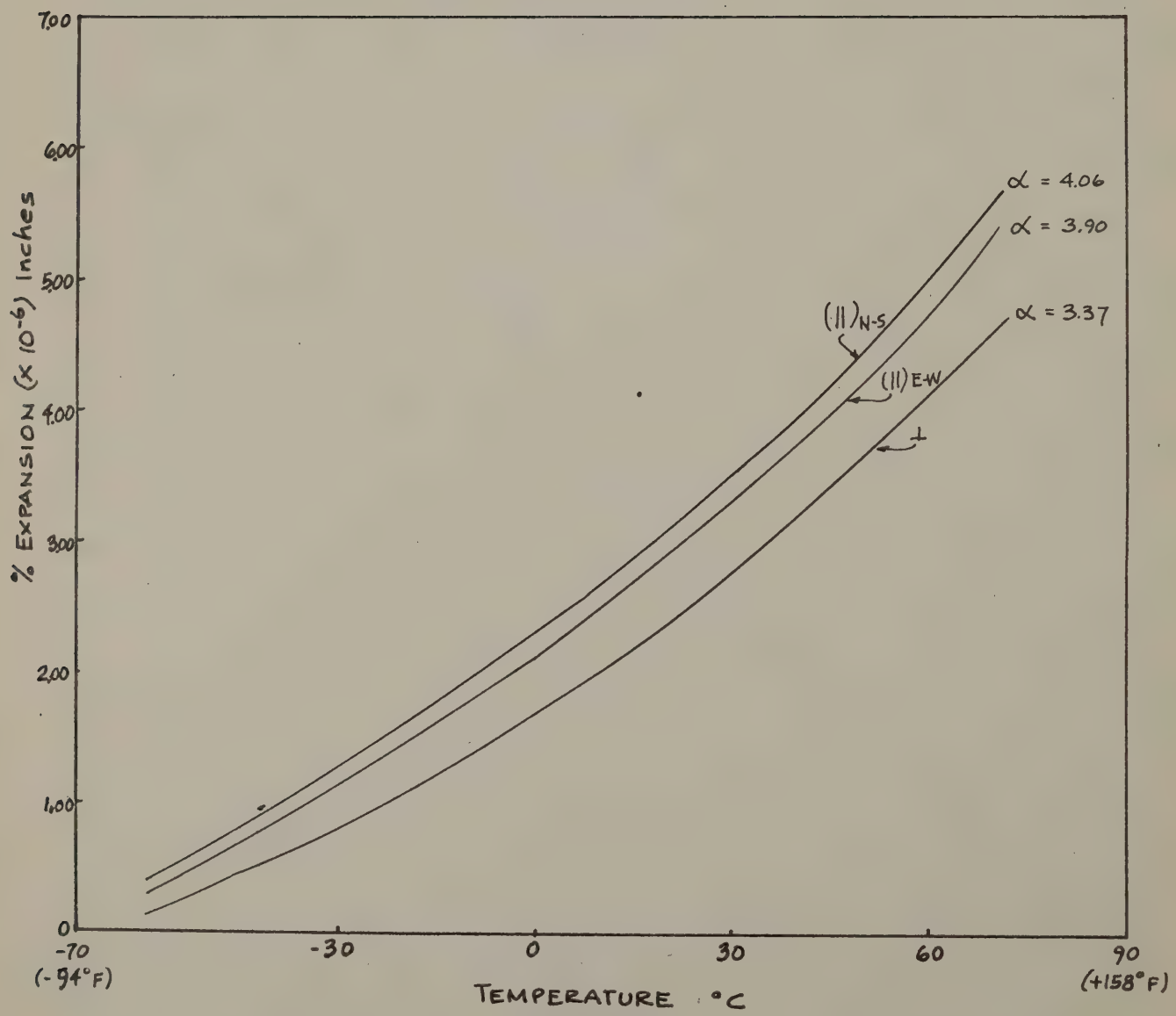


# THERMAL EXPANSION CURVE
# FOR SAMPLE 24-Ec



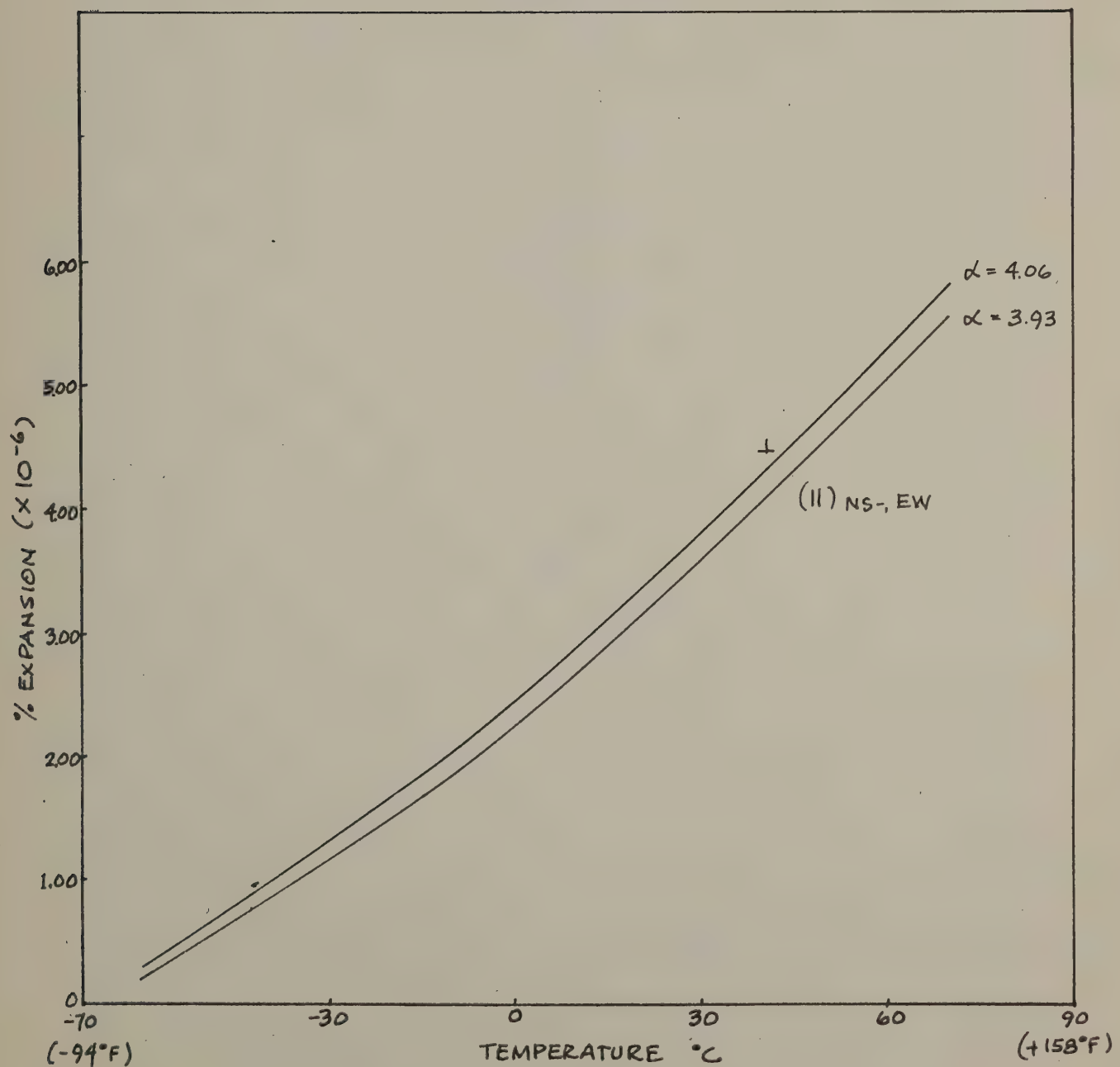
# THERMAL EXPANSION CURVE

## FOR SAMPLE E-2

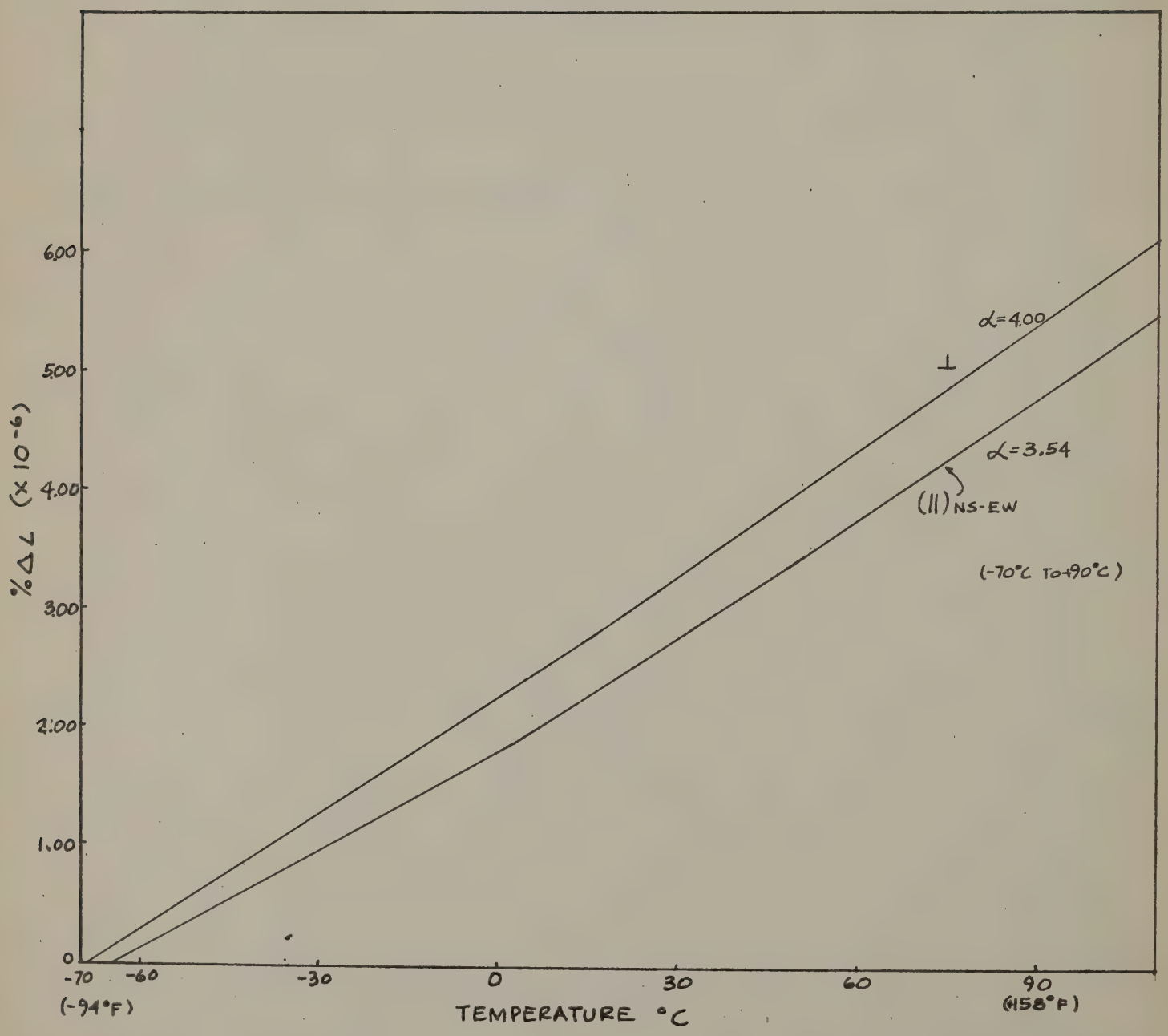


# THERMAL EXPANSION CURVE

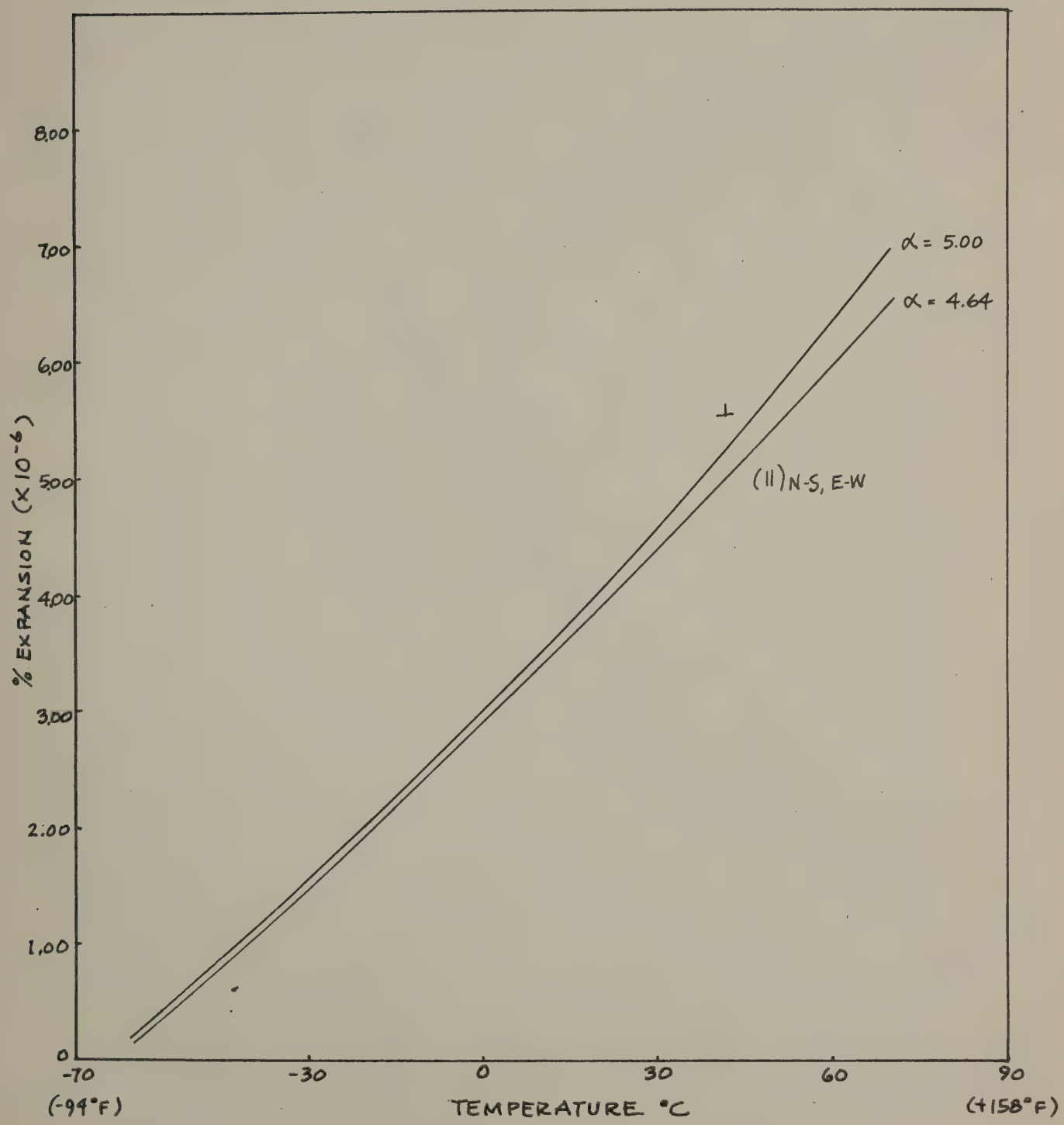
## FOR SAMPLE OL-2



# THERMAL EXPANSION CURVE
## FOR SAMPLE 34-1

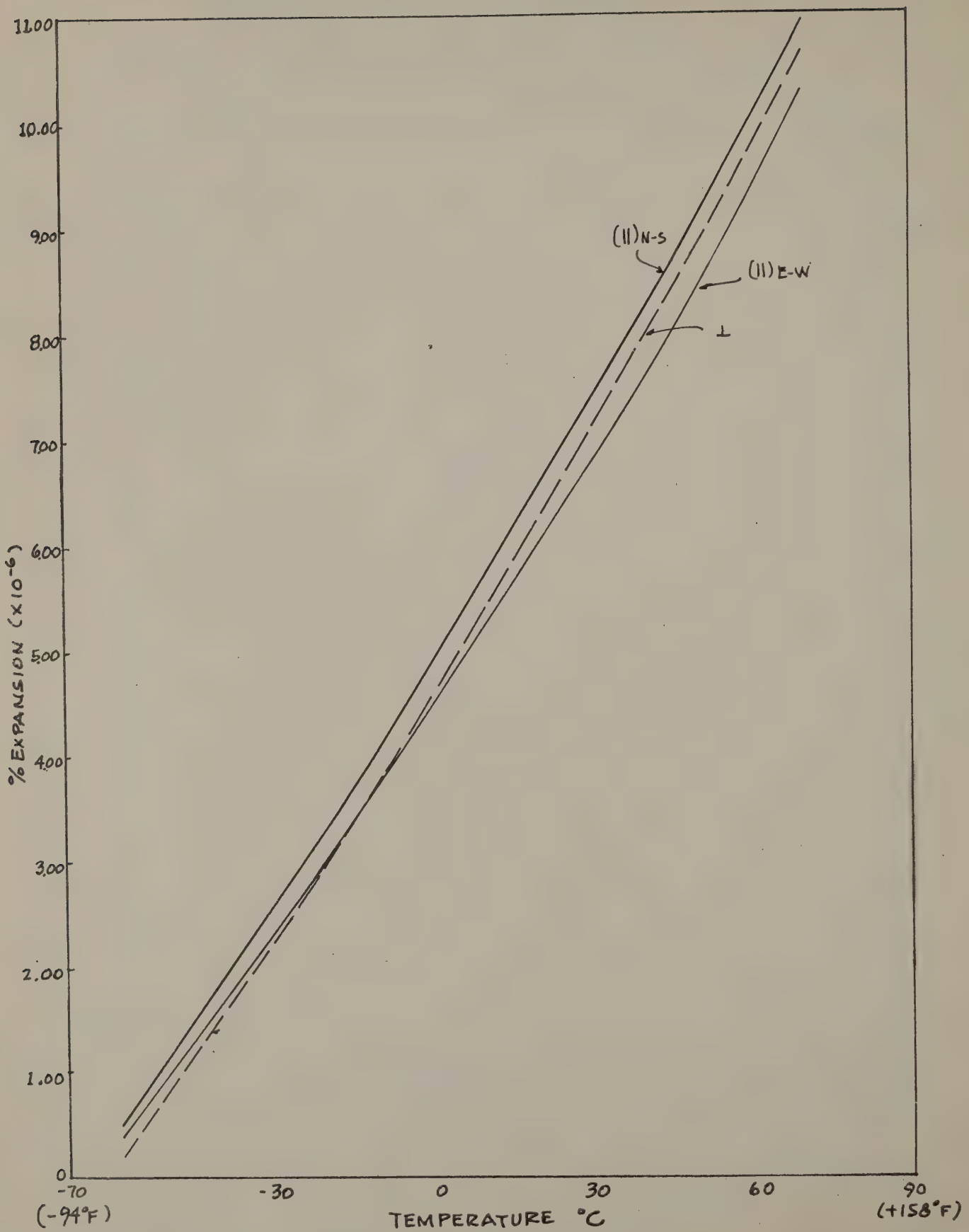


# THERMAL EXPANSION CURVE FOR SAMPLE R-2



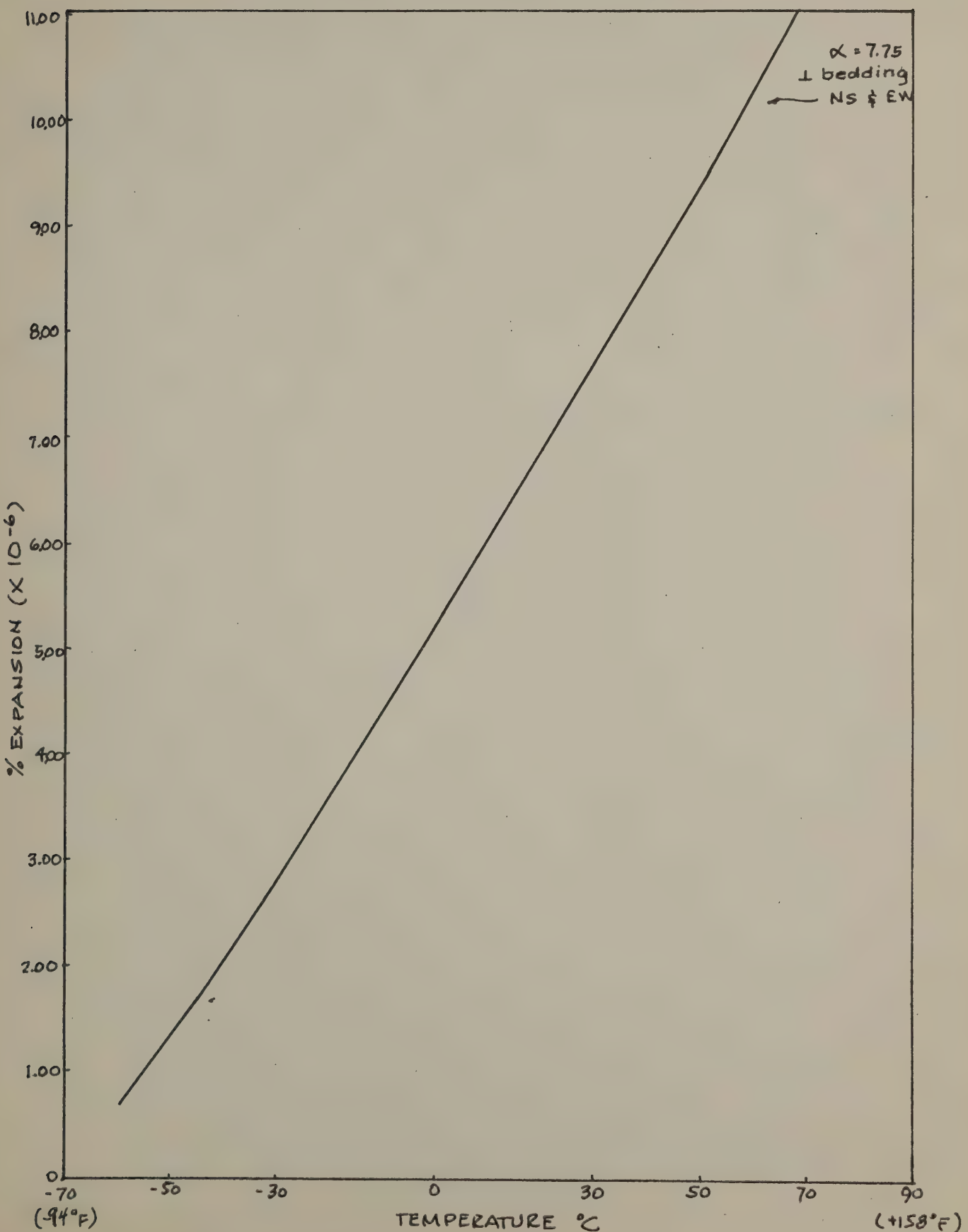
# THERMAL EXPANSION CURVE

## FOR SAMPLE K-2

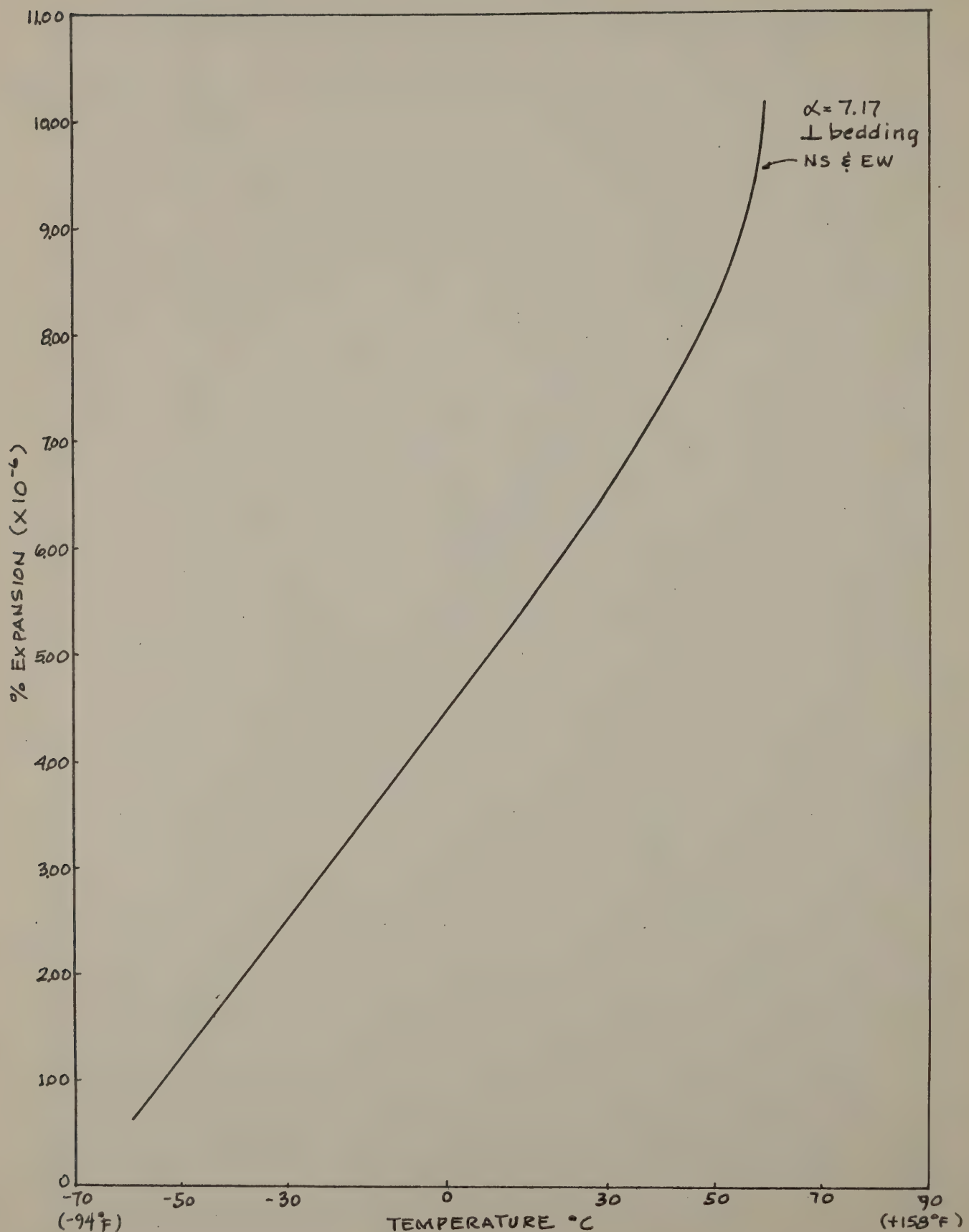


# THERMAL EXPANSION CURVE

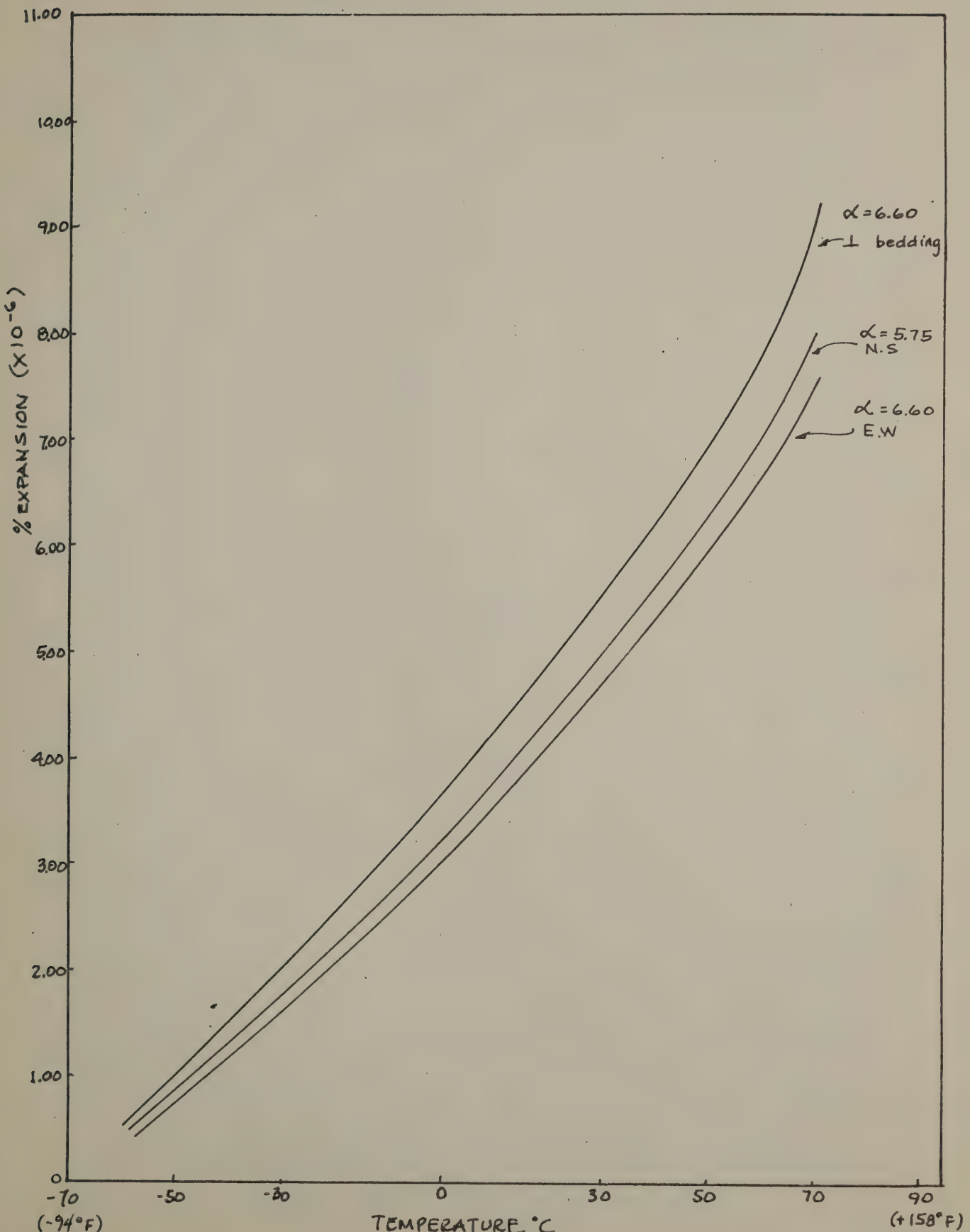
## FOR SAMPLE OF OAK ORCHARD GATES - 6C

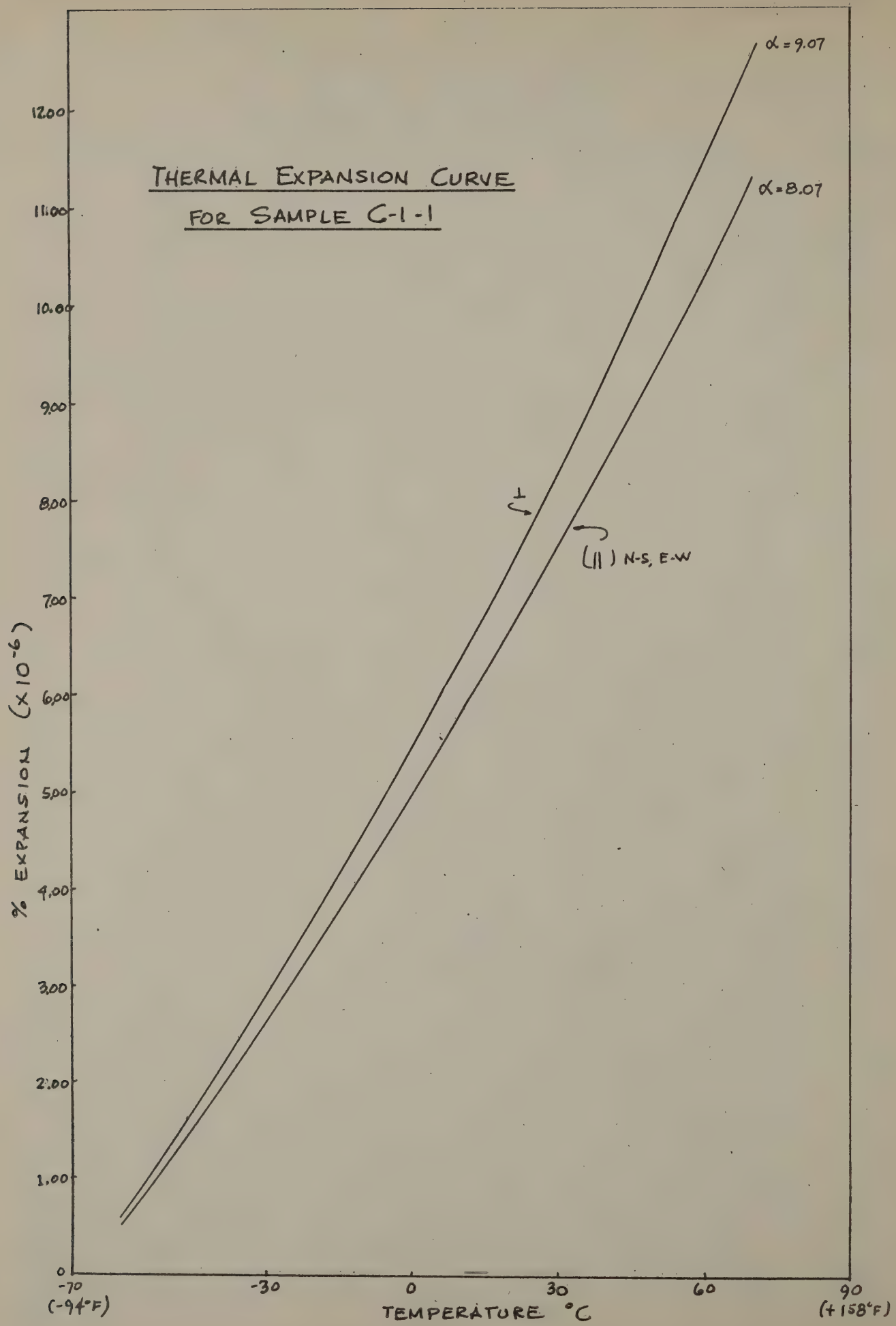


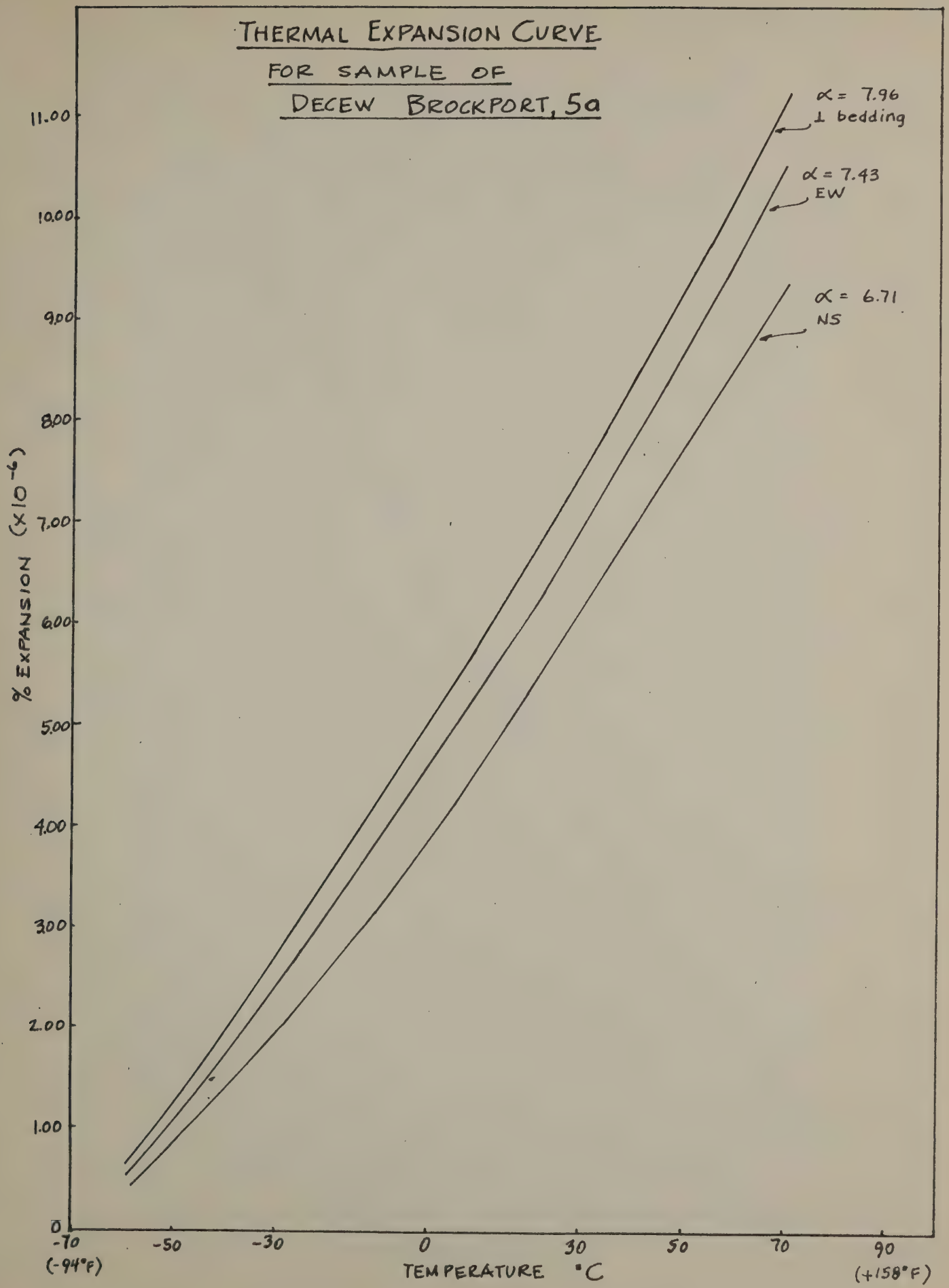
# THERMAL EXPANSION CURVE
## FOR SAMPLE OF GOAT ISLAND (2 DU) LOCKPORT

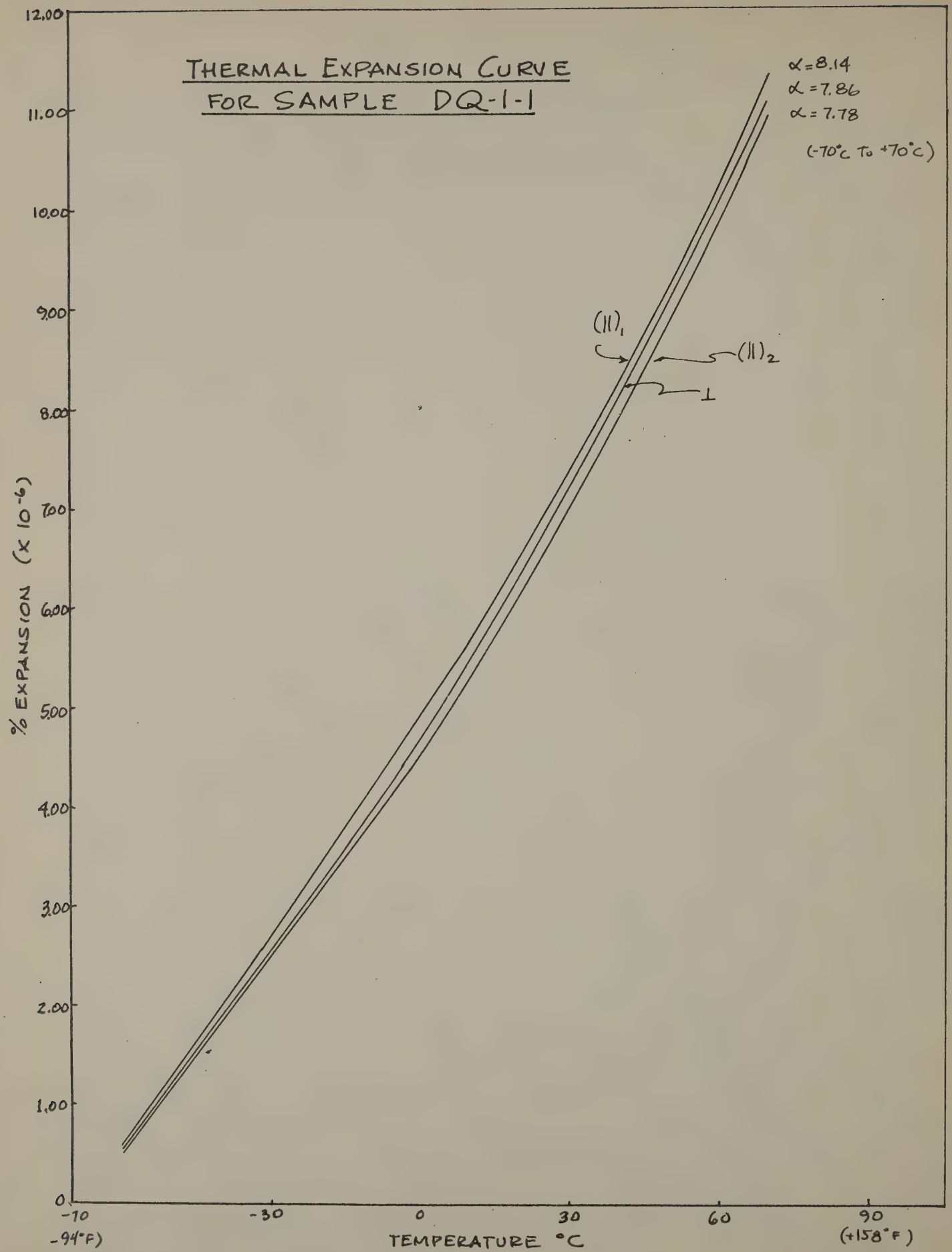


# THERMAL EXPANSION CURVE
## FOR SAMPLE OF
## BROCKPORT LIMESTONE, 5b



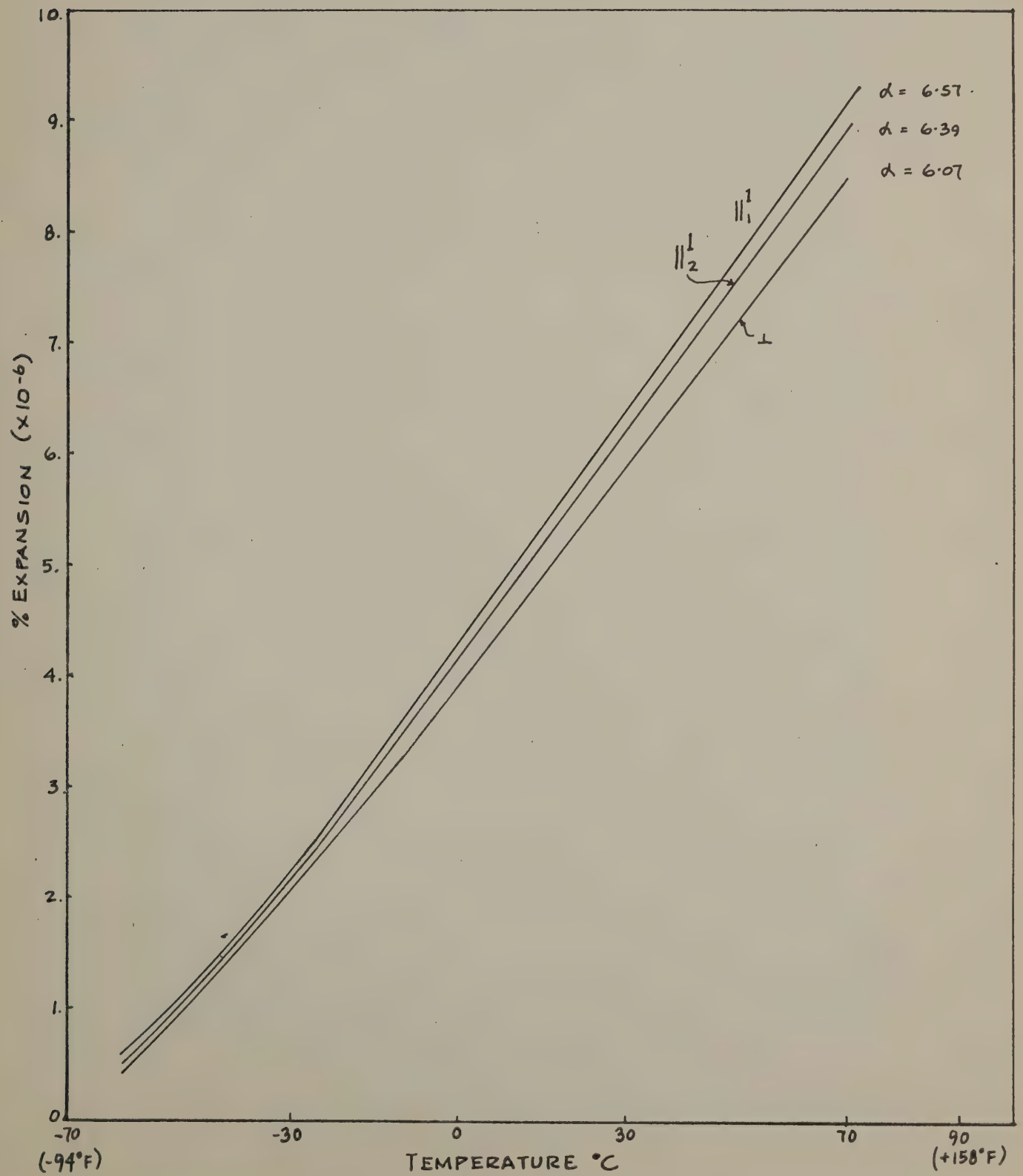

THERMAL EXPANSION CURVE
FOR SAMPLE C-1-1
α = 9.07
α = 8.07
⊥
(11) N-S, E-W
% EXPANSION (X 10⁻⁶)
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0
-70
(-94°F)
-30
0
30
60
90
(+158°F)
TEMPERATURE °C


THERMAL EXPANSION CURVE
FOR SAMPLE OF
DECEW BROCKPORT, 5a
α = 7.96
⊥ bedding
α = 7.43
EW
α = 6.71
NS
% EXPANSION (X10⁻⁶)
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0
-70
(-94°F)
-50
-30
0
30
50
70
90
(+158°F)
TEMPERATURE °C


THERMAL EXPANSION CURVE
FOR SAMPLE DQ-1-1
α = 8.14
α = 7.86
α = 7.78
(-70°C To +70°C)
(||)1
(||)2
⊥
% EXPANSION (X 10⁻⁶)
12.00
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0
-10
(-94°F)
-30
0
30
60
90
(+158°F)
TEMPERATURE °C

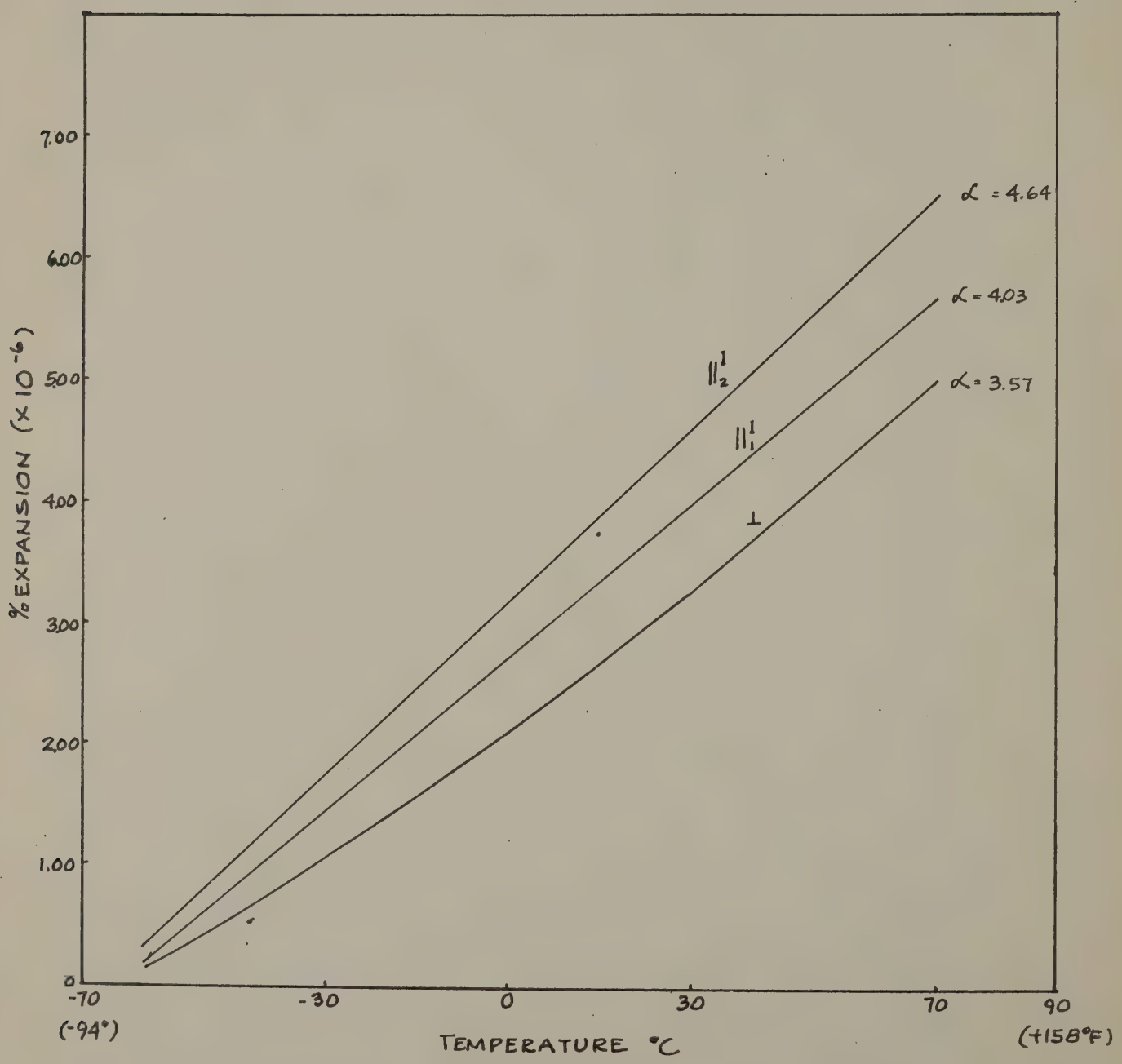
# THERMAL EXPANSION CURVE

## FOR SAMPLE P-B-2



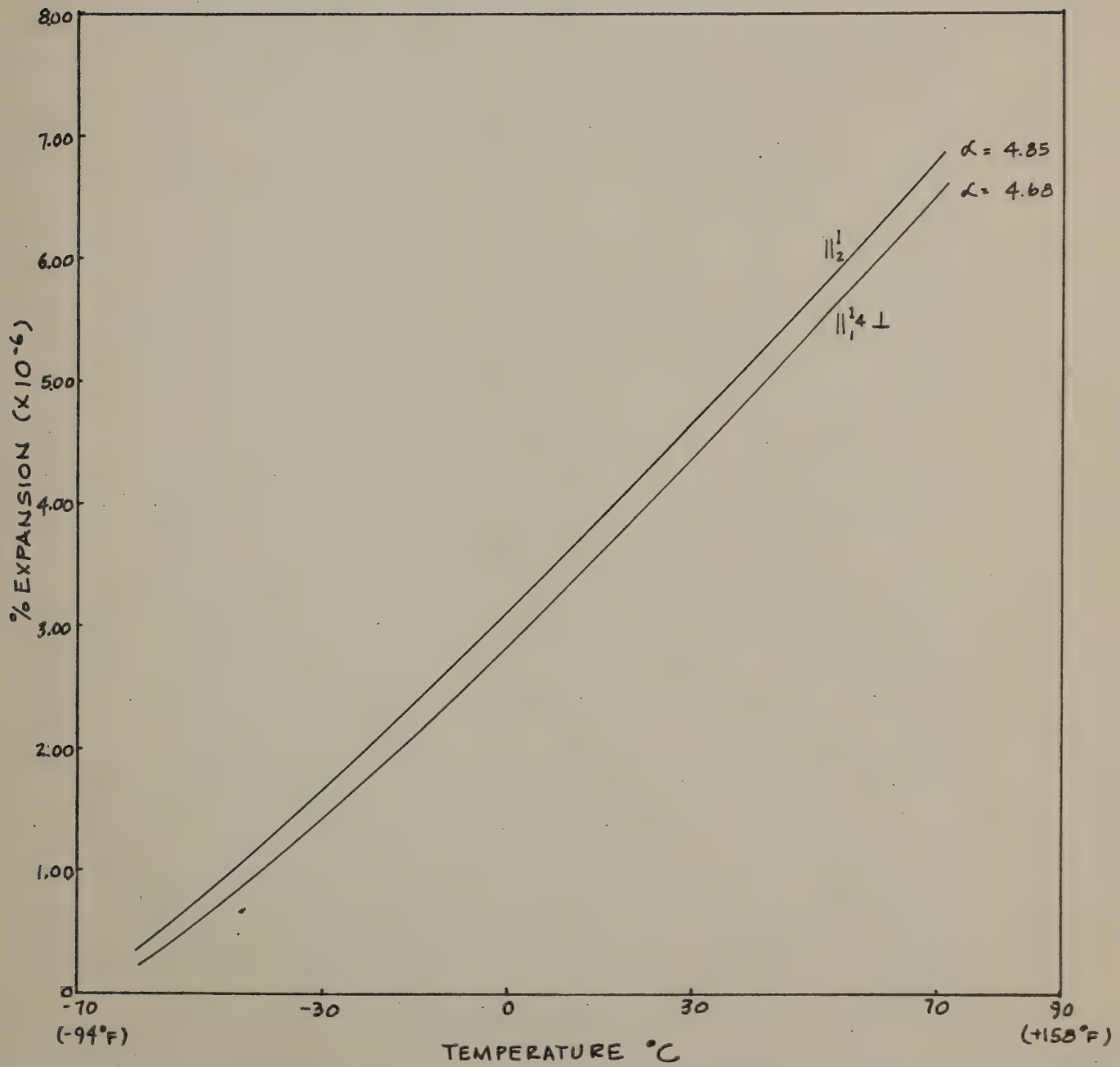
# THERMAL EXPANSION CURVE

## OF SAMPLE P-B-1

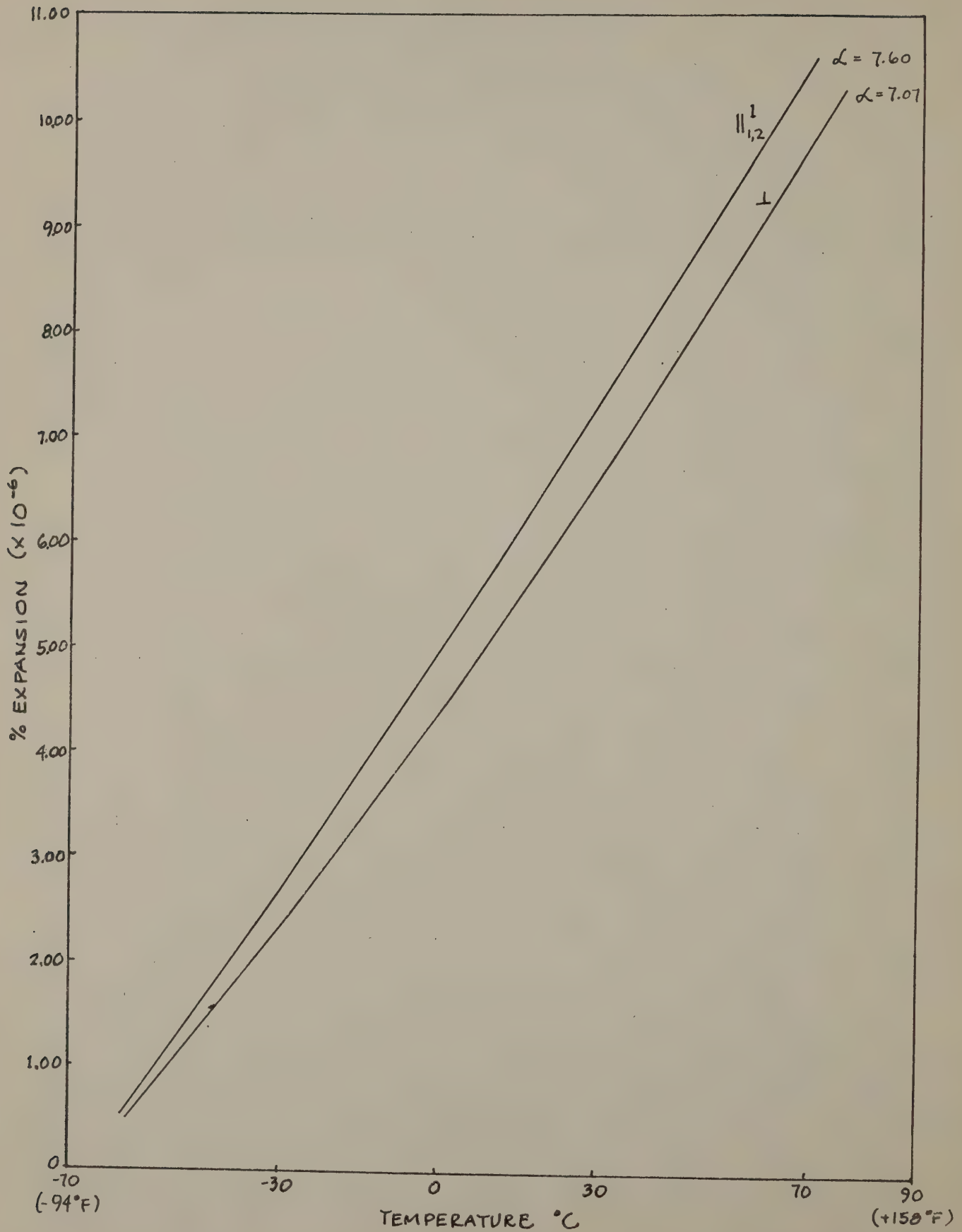


# THERMAL EXPANSION CURVE

## FOR SAMPLE P-A-2



# THERMAL EXPANSION CURVE
# FOR SAMPLE P-A-1



# APPENDIX D

## FREEZING AND THAWING IN CONCRETE, SOME SPECIAL CASES

## FREEZING AND THAWING IN CONCRETE, SOME SPECIAL CASES

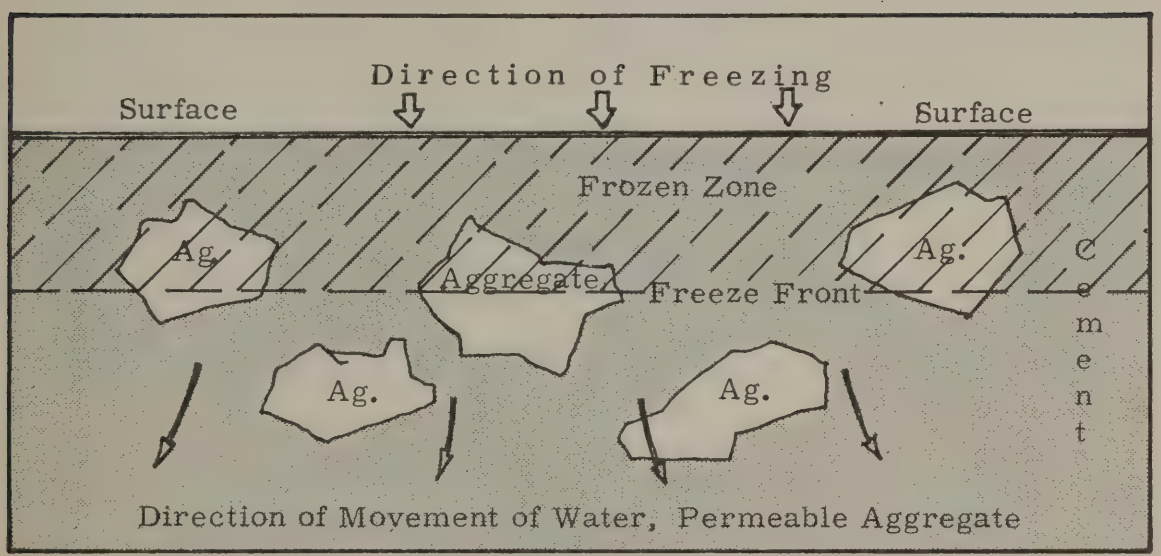
### Introductory Statement

A series of special cases are presented here to demonstrate the applicability of some of the hypothetical parts of this paper to specific conditions.

In some of these examples the assumption is made that saturated cement paste is capable of transmitting water without disrupting. As noted previously in this paper and as noted by Verbeck and Landgren (1960), it is questionable that saturated cement paste can transmit major quantities of liquid water under pressures lower than its tensile strength. It was also indicated by Verbeck and Landgren that the greatest disruptive pressures probably occur when the cement paste itself is saturated and then freezes. However, until such hypotheses are more clearly demonstrated experimentally, it will be assumed that cement paste can transmit water under certain postulated conditions.

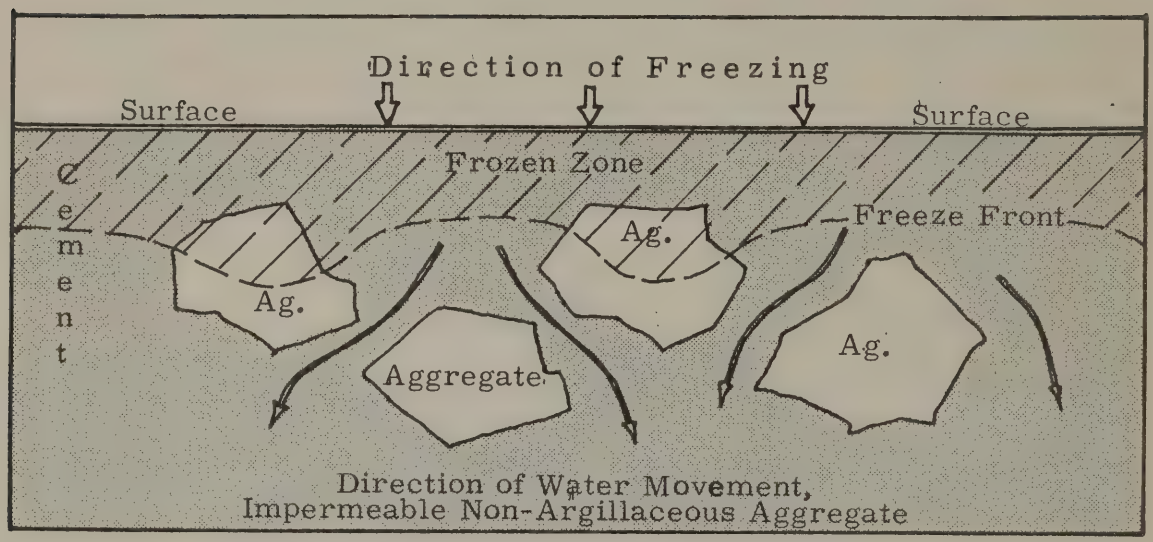
Illustrated Examples

Case 1: Aggregate and portland cement with similar thermal and pore characteristics, both saturated.



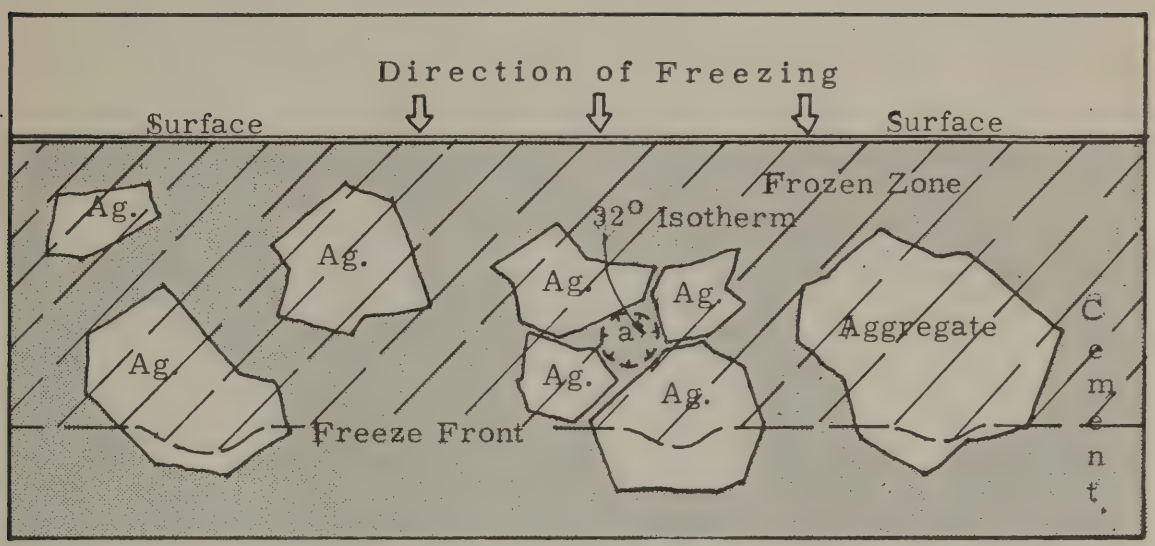

Water moves evenly ahead of the migrating ice front directly away from the freezing surface. No distress.

Case 2: Aggregate, impermeable, and portland cement, water saturated.




The high water content of saturated portland cement (10% or so) means that the rate of cooling of the paste would be much slower than that of the aggregate. Potential pockets of non-frozen water in the paste could later freeze and disrupt the concrete.

Case 3: Aggregate saturated and with high thermal conductivity in saturated portland cement paste.

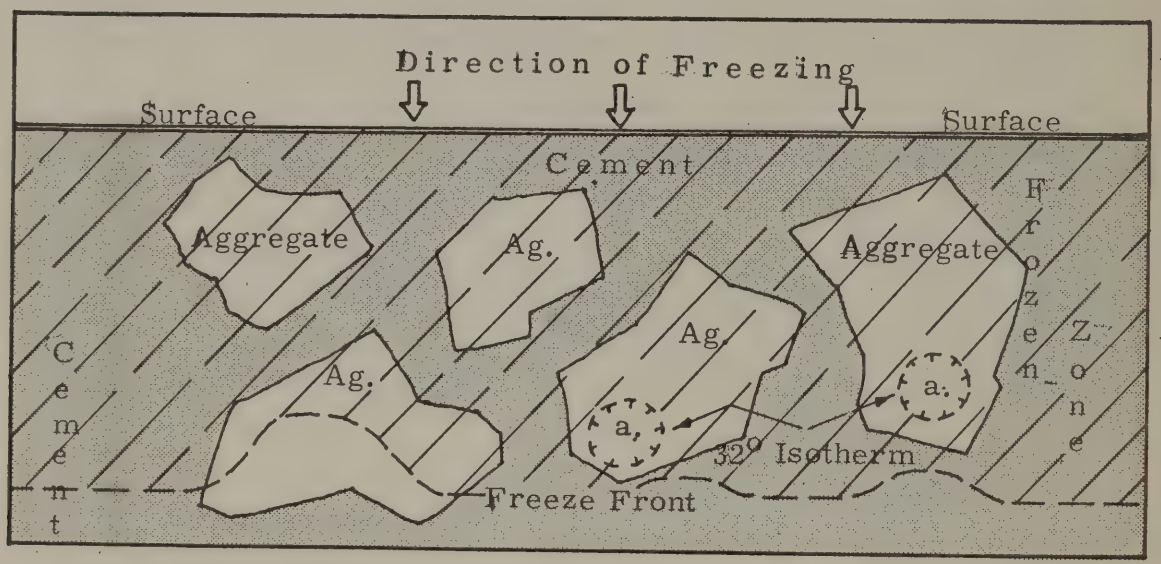



A deleterious effect could occur if the thermal conductivity of the aggregate were high enough to increase the rate of movement of the ice front and the rate of water expulsion to a greater extent than could be transmitted by the cement paste.

Typical thermal conductivities: In mcal/cm/sec/°C limestone 6.77 dolomite 11.37 (Robertson, 1959); ice 2.14 (Pounder 1960)

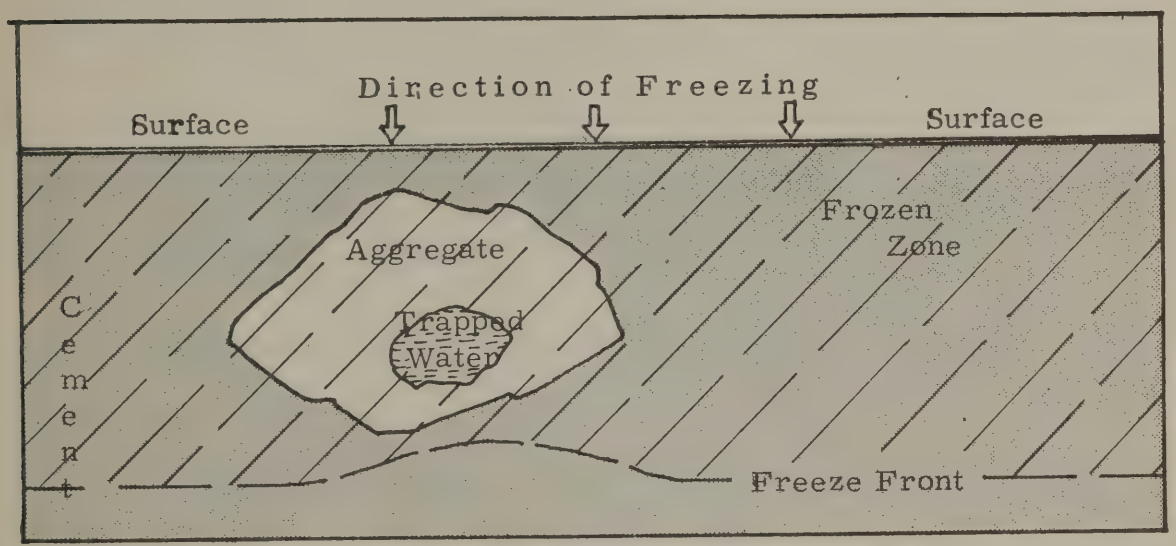
Case 4: Thermal conductivity of the aggregate far less than that of the portland cement, both saturated.

Diagram 6 below shows the possible position of isotherms where the aggregate has a much lower heat conductivity than the portland cement.



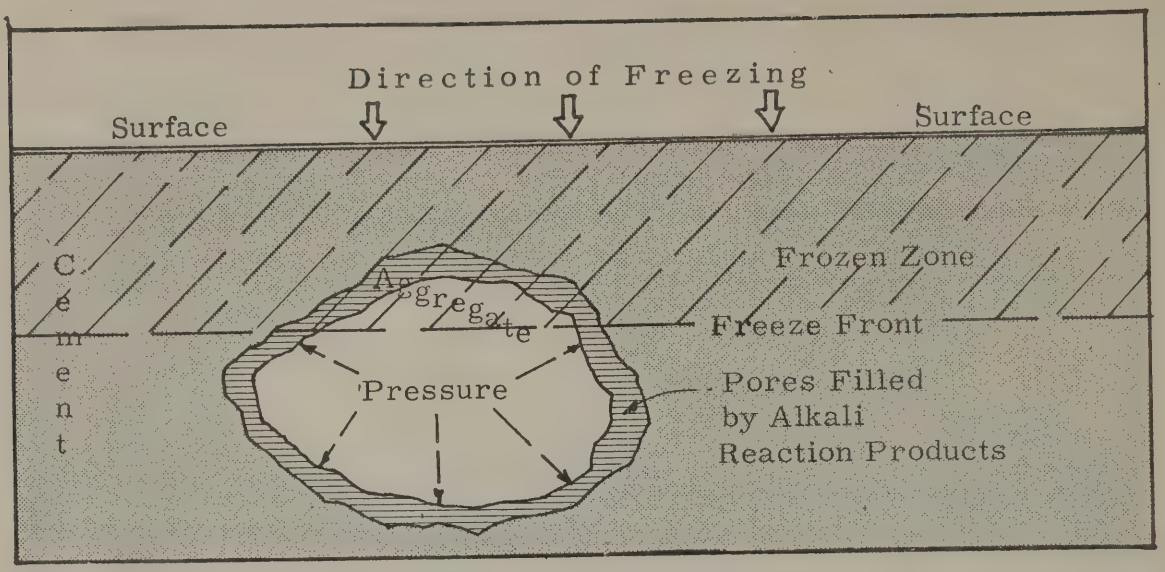

When the aggregate is a very poor heat conductor, the heat loss may allow pockets of non-frozen water (a, above) to remain after the immediately surrounding concrete is completely frozen. Later freezing of such zones would cause radial disruptive forces.

Case 5: A single particle of critically saturated aggregate with 10% porosity, surrounded by paste and aggregate with low water content, say less than 1%.




The cooling rate of the particle would be about 10 times slower than the surrounding material because of the high water content. The 32°F zone could migrate well past the particle and ultimately freezing could occur at the bottom of the particle, trapping water in ice. Hydrostatic and ice pressures could then become disruptive when the water finally freezes.

Case 6: A critically saturated alkali-reactive aggregate particle with high porosity in any environment.




Disruption could occur here when freezing occurs, because the water would be unable to escape the particle during freezing. An example of this situation could be chert #45 from western New York (Dunn and Ozol, 1962). Chert similar to #45 was responsible for every "pop-out" in a highway in western New York over a considerable distance. Alkali-reactivity was considered to be a contributing cause to the pop-outs. Quick chemical tests disclosed that it was well within the range of potentially reactive materials yet in a mortar bar chert #45 was the only chert studied which did not cause deleterious expansion. (.055% in eleven months). But chert #45 had a water absorption of 3.89% by weight, over four times that of the second most absorptive chert. It also had the lowest bulk specific gravity (dry basis). It is suggested that the pores of chert #45 were filled with reactant products which prevented excessive mortar bar expansion. Such reactant products, however, may also have prevented egress of water in exposed concrete in the highways and freeze-thaw failures then became possible.

Miscellaneous Cases, Assuming Saturation

1. Pockets of non-freezing may occur under wood in a concrete structure. Heat conductivity, K, in B.T.U. per hour per square foot at temperature gradient of one degree Fahrenheit per inch thickness, for common woods varies between 6 and 9 (Handbook of Chemistry and Physics), far less than stone or concrete.

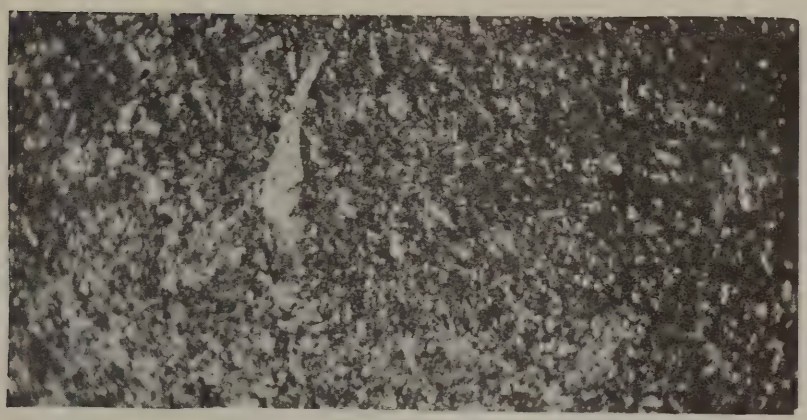
2. Thermal conductivities of limestone and sandstone are similar to the average for concrete, but marble and granite have two or three times the conductivity of normal concrete (Handbook of Chemistry and Physics). It might be anticipated that concrete containing heterogeneously mixed aggregates such as sandstone and granite could have deleterious thermal conductivity conditions.

3. Structural steel exposed in the air could, under some circumstances, have dangerous thermal reversals. The thermal conductivity of steel is 0.108 to 0.115 calories/second/$cm^2$/cm length whereas the average thermal conductivity of concrete is 0.0022/second/$cm^2$/length. (Handbook of Chemistry and Physics).

# APPENDIX E

# PETROGRAPHY

Jamesville Member - Sample E-a-1

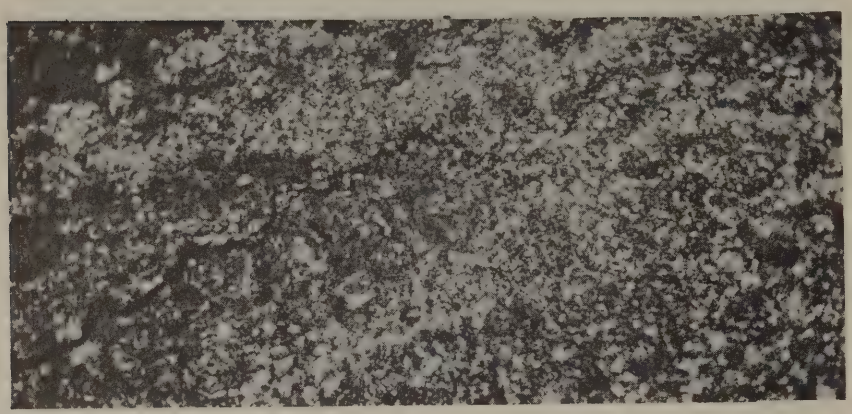


U X P

0.5 mm

Sample E-a-1 is typical Jamesville and consists of relatively homogeneous microcrystalline calcite with minor sparry fossil remains. About 2% of the section is clear dolomite rhombs and the black spots are probably iron oxides. The dark cast results from disseminated carbonaceous material and clay.

Jamesville Member - Sample 24-J-1

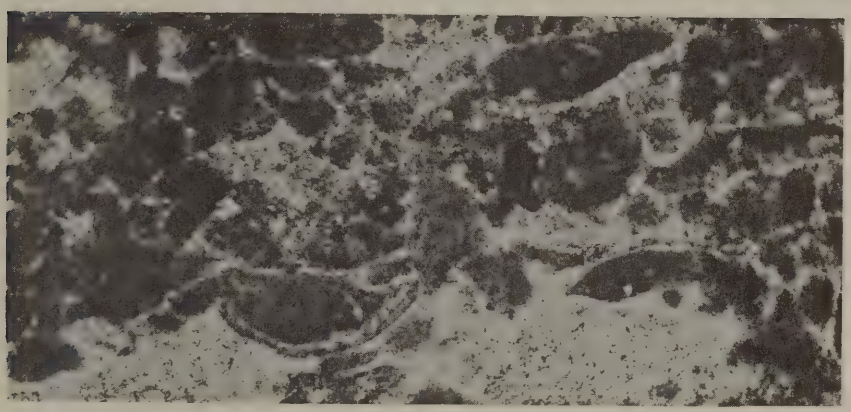


Plane light

0.5 mm

Banded very fine-grained stylolitic limestone. The groundmass is composed of very dark aggregates of microcrystalline "ooze" (about 70%) within which are dolomite rhombs, (about 10%) (.05 mm avg., range from .03 to .07 mm), quartz-silt grains (about 2-3%), and localized zones of sparry calcite. The structure of the slide is of bands of dark, microcrystalline limestone alternating with bands of lighter colored microcrystalline limestone bearing a higher percentage of dolomite and quartz. The quartz occurs as fine silt in the .008 to.016 mm size range. The sparry calcite occurs as islands or patches irregularly distributed throughout the limestone. Each island usually contains several coarse grains of calcite about .3 mm in diameter.

Clark Reservation Member - Sample 34-3-1



U X P

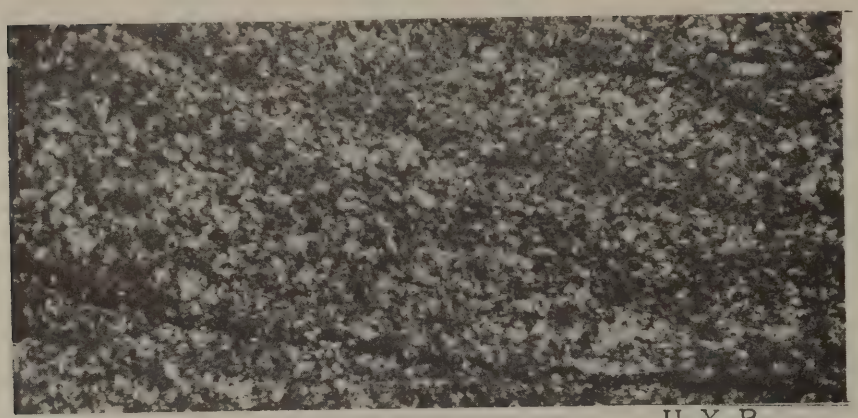
0.5 mm

The rock is a pelletiferous, stylolitic limestone consisting of rounded, spherical to ovoid aggregates of internally structureless, microcrystalline calcite "ooze" in a groundmass of interstitial, sparry calcite. The pellets are about 0.25 mm avg. size (range from 0.05 to 0.4) across the longest diameter. There are many zones in which ovoid pellets are aligned with their long axes parallel. The pellets may merge into areas of microcrystalline calcite ooze matrix. The pellets and the "ooze" constitute about 70% of the thin-section. The sparry calcite (about 20%) grades into local pellet free areas about 0.5 mm across.

Fossil fragments (about 10%) may be oomposed of relatively coarse to micro-crystalline, sparry calcite. There is very little clastic material.

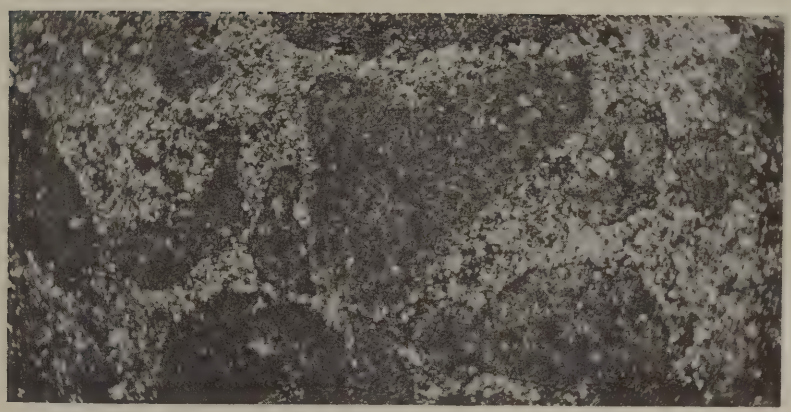
The rock is generally similar to 34-1-2 but differs in that the pellets are more abundant, larger, and more tightly compacted. Also, no detrital quartz grains were noted.

Clark Reservation Member - Sample 24-CR-1




The groundmass (about 80%) is composed of indistinct, murky aggregates of microcrystalline ooze within which are set dolomite rhombs (about 10%) (0.06 mm avg., range from 0.04 to 0.08) and quartz sand and silt grains (.1mm avg., range from 0.04 to 0.16). The section has many zones composed of alternate laminations (about 0.5 mm thick) of darker colored, apparently argillaceous bands, and lighter colored dolomite and quartz-silt bearing bands. The quartz grains (1-3%) are sub-angular to sub-rounded, and are evenly distributed except for their concentration in streaks or laminations as noted above. The laminations are accentuated by thin, crenulated ("microstylolitic") black carbonaceous and argillaceous partings.

Elmwood C - Sample R-1-1



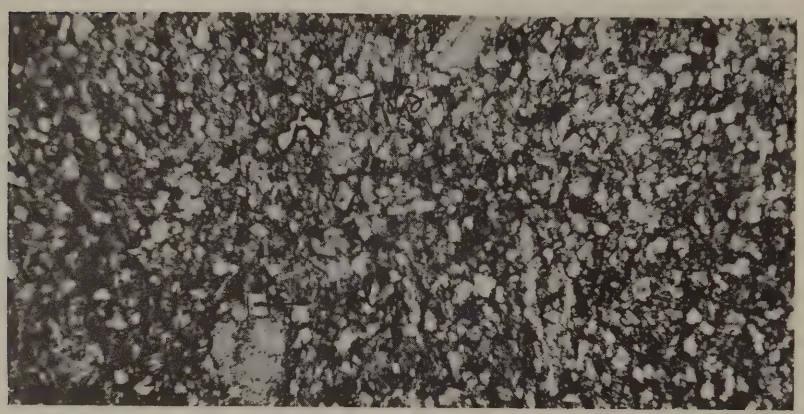
Plane light

0.5 mm

The rock has a clastic appearance and parts of it look like a micro-conglomerate with limestone and dolomite intraclasts of 2:1 ratio. The groundmass is composed of microcrystalline calcite and fine, euhedral dolomite.

The intraclasts are irregularly shaped and range in size from 0.2 to 2.0 mm and are restricted to certain zones. The dolomite locally is in thin bands of laminae. The intraclasts are elongated along the bedding plane. Dolomite, 60%, calcite 30%, quartz and clay about 10%.

Elmwood B Sub-member - Sample E-2



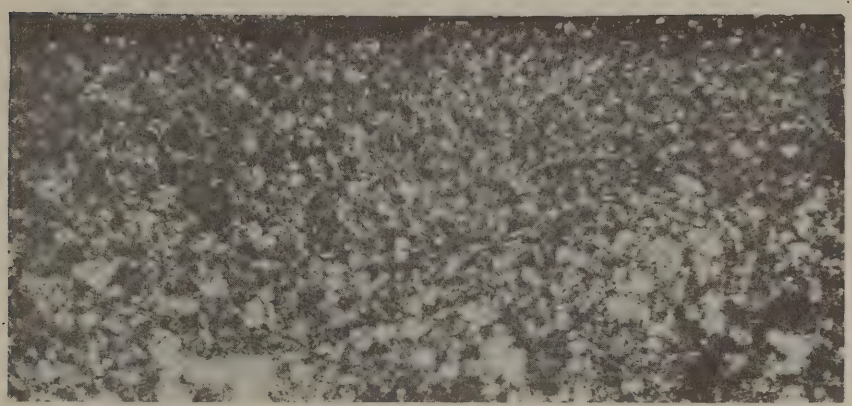
Plane light

0.5 mm

Sample E-2 is a pelletiferous, fossiliferous limestone, the pellets comprising about 20%, diameter 0.05 mm. Clear, dolomite rhombohedra (0.05 mm) are about 5% of the slide. The dark groundmass consists of microcrystalline to sparry calcite. Quartz silt is about 3%. Recognizable fossils are mainly crinoid stems.

Manlius
Formation

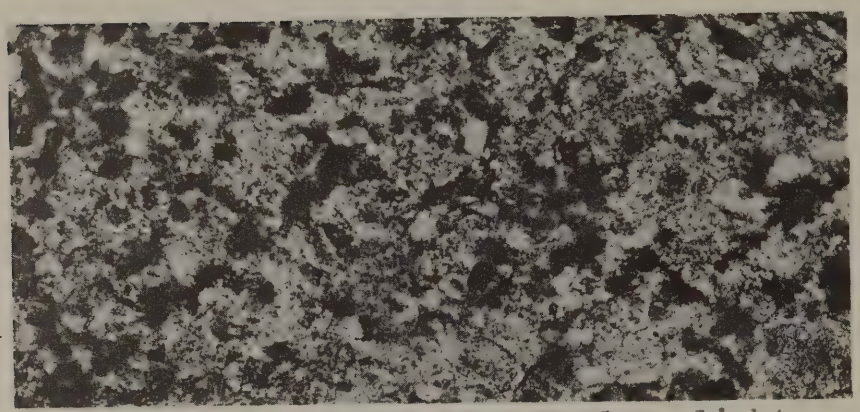
Elmwood A. Submember - Sample 24-Ea-1



0.5 mm

Laminated, banded, very fine-grained limestone. The laminations are 0.2 to 2 mm thick and are accentuated by thin carbonaceous, "microstylolitic" lines. The groundmass is composed of microcrystalline calcite which is aggregated into indistinct, irregularly shaped "clumps" about .008 mm across. Within the groundmass are quartz silt, dolomite rhombs, and patches of sparry calcite. The dolomite rhombs (about .05 mm avg. size) appear to be locally concentrated in certain laminations, but also occur distributed throughout the section. The quartz silt (.06 mm) occurs distributed throughout the section. The "islands"of sparry calcite are irregularly shaped and irregularly distributed throughout the thin section. They are about 0.5 to 1.5 mm across and usually contain several grains of coarse sparry calcite. Accumulations of fossil debris in local zones are associated with disturbed bedding.

Olney Member - Sample 34-1-2



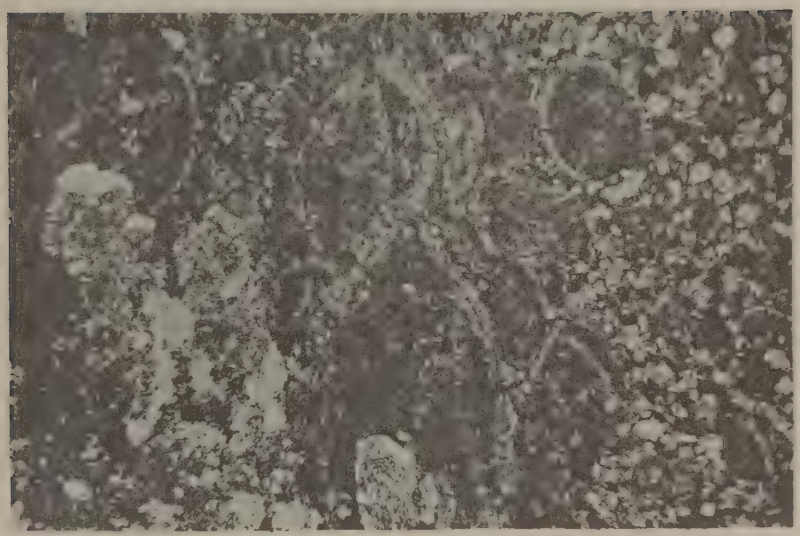
Plane light

0.5 mm

The rock is a pelletiferous limestone consisting of rounded, spherical to elliptical or ovoid aggregates of microcrystalline calcite ooze, (about 40%) devoid of any internal structure, set in a groundmass of interstitial sparry calcite. The sparry background (about 55%) may grade into local pellet free areas about 1 mm across which contain coarse (.1 to .4 mm) grained calcite. The pellets are fairly well sorted (avg. size .07 mm, range from .04 to .1 mm) and regular in shape. A few are irregular. Evenly distributed throughout the thin-section are angular to sub-angular clastic quartz silt and sand grains. Their average size is .07 mm (range from .04 to .2 mm) and they constitute about 5% of the thin-section.

Localized concentrations of fossil debris consist of small curved shells about .5 mm long, with their long dimensions aligned parallel to the bedding. A few larger fossil fragments (probably of corals) are present.

Thacher Member - Sample R-2



U X P

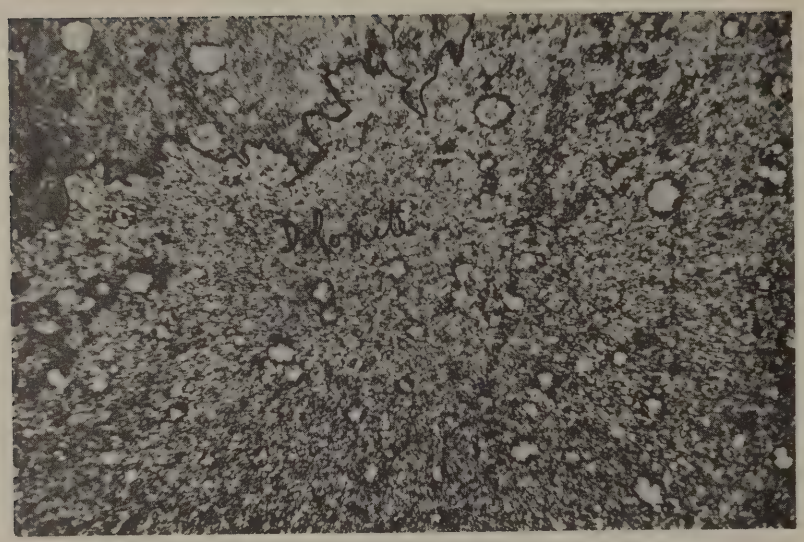
0.5 mm

R-2 is a highly fossiliferous, dolomitic limestone. The dolomite is finely crystalline (0.04 mm). The rest is composed of micro-crystalline calcite groundmass.

Dolomitic and calcitic laminae are interlayered. Also fossiliferous and non-fossiliferous layers are visible from top to bottom. In some parts of the thin-section veinlets of dolomite cut into the calcite-dolomite layers.

Cobleskill
Formation

Sample K-2

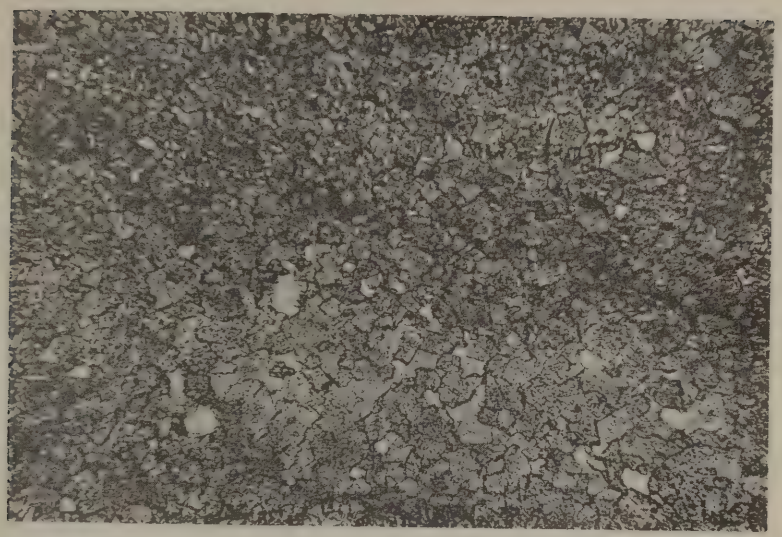


Plane light

0.5 mm

The Cobleskill is a dolomitic with over 60% fine-grained (0.02 mm) dolomite which is in the form of nodules, veins and bands. The boundary between this dolomite and the neighboring calcite cement (35%) is sharp. The calcite cement is also specked with dolomite crystals. The clay component seems to be disseminated evenly throughout the slide.

Oak Orchard Member - Sample 1b

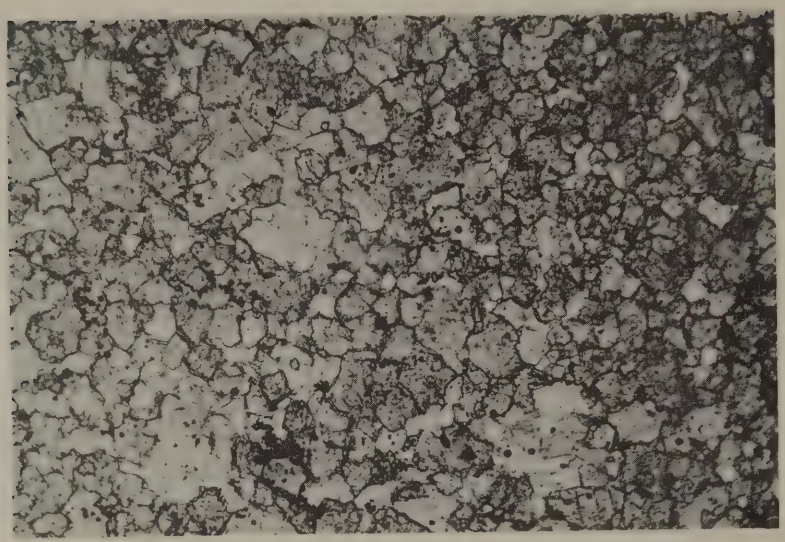


Plane light

2.0 mm

The sample consists predominantly of dolomite which is fairly fine-grained (0.01 to 0.1 mm) and is subhedral to euhedral. There is a scattering of quartz grains, about 1-2%, and some argillaceous material occuring along microstylolites. No recognizable fossils were seen.

Eramosa Member - Sample 1a

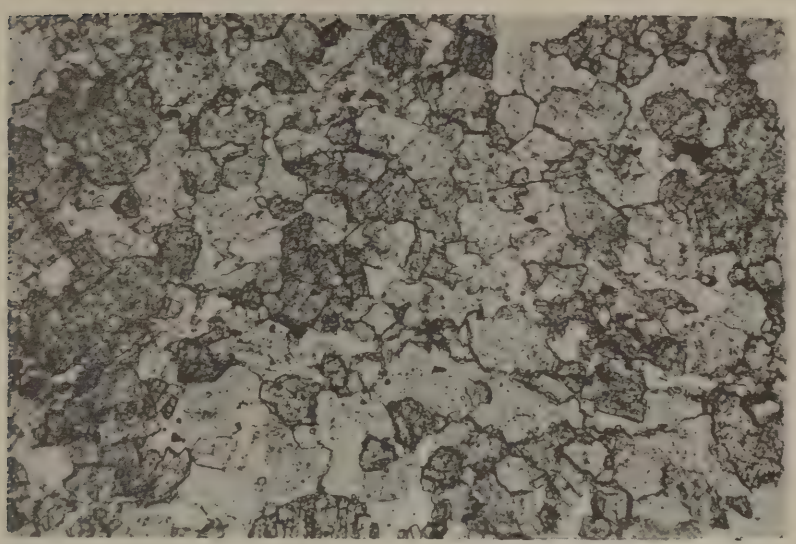


Plane light

2.0 mm

Sample 1a is an argillaceous dolomite, dolomite crystals subhedral, 0.1 to 1.0 mm. Quartz as irregularly-shaped, corroded grains is about 2%. Carbonaceous and argillaceous material occurs as blebs and stringers between grains and along edges of replaced fossil debris.

Goat Island Member - Sample 4c

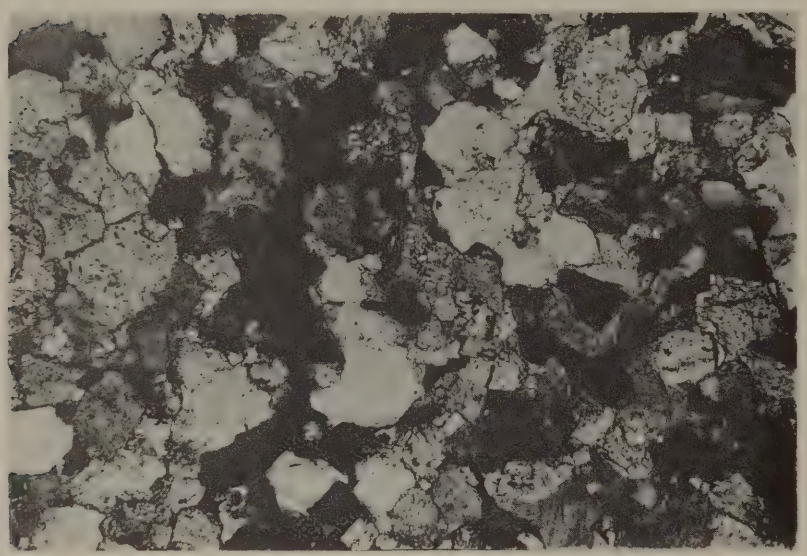


Plane light

2.0 mm

About 20% of the rock is composed of anhedral quartz averaging about 0.3 mm. The carbonate is predominantly subhedral dolomite, 0.7 - 1.2 mm. Fossil fragments and a bit of chert occur as well.

Penfield Member - Sample 6a

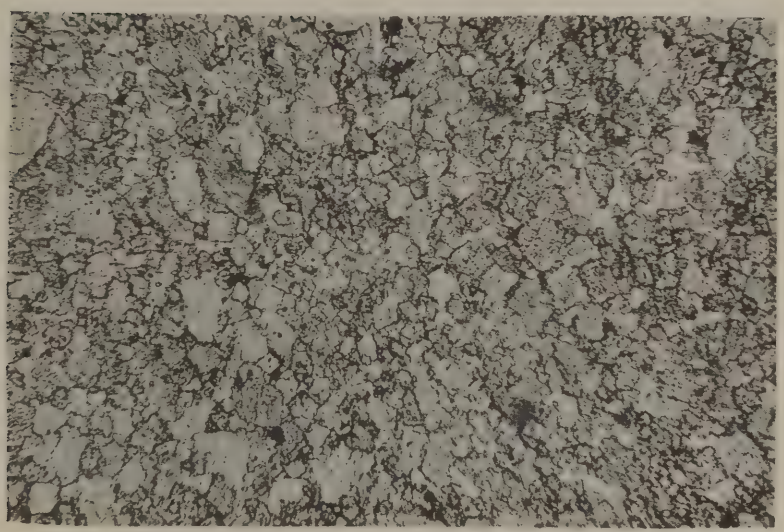


U X P

2.0 mm

This rock is a dolomite with nearly 40% quartz sand. The quartz grains are anhedral and about 1.5 mm in size. The carbonate is mostly subhedral dolomite, 0.5 to 1.5 mm in size. Some microstylolites and crinoid stems were noted.

C-Unit, Gasport Member - Sample 2c



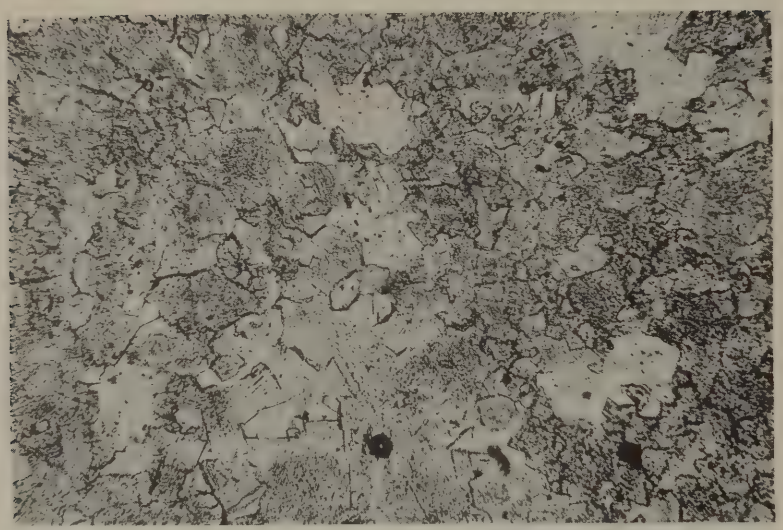
Plane light

2.0 mm

Section 2c is primarily euhedral to subhedral dolomite (0.5 - 1.0 mm) with about 5% interstitial calcite. A few pores can be seen.

Some sphalerite and galena and traces of hematite and fossil remains and a few quartz grains form the minor constituents of the rock. It is a fairly homogeneous dolostone. Dark brownish clay partings and peripheral rims are common.

Gasport Member - Sample 2b

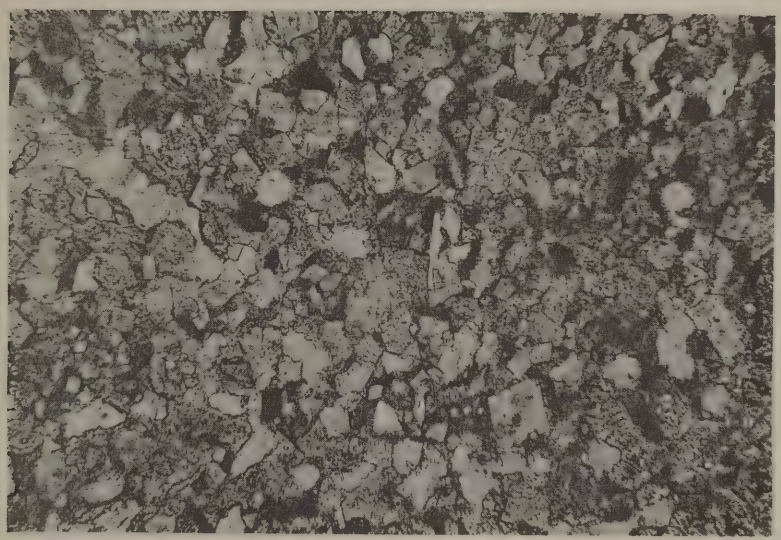


Plane light

2.0 mm

Except for about 5% calcite, this rock is composed of subhedral dolomite 1.0 - 2.0 mm. A few quartz grains and a little clay are also present. This rock is composed mostly of recrystallized fossil debris with some crinoid stems still recognizable. It is fairly porous.

Gasport Member, Brockport Lentil - Sample 5b



Plane Light

2.0 mm

This rock is a medium-grained, siliceous limestone which contains fossil fragments. Quartz (25%) occurs as grains 0.05 to 0.25 mm. The carbonate is sparry calcite (0.6 mm) and fine (0.01 - .05 mm), interstitial calcite with scattered dolomite enhedra (0.5 - 1.0 mm).

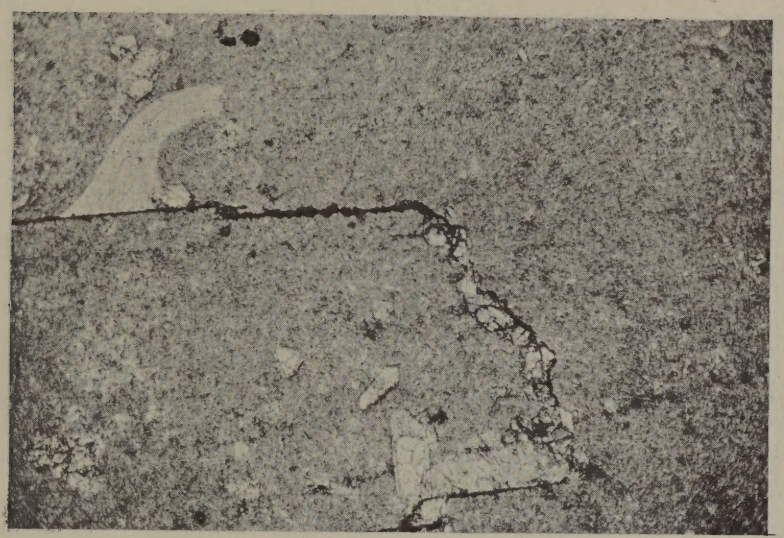
Decew Member - DQ-1-1

Plane Light

2.0 mm

DQ-1-1 is a homogeneous dolomite. It consists of irregularly arranged euhedral and some anhedral dolomite (79%) rhombs (average size 0.05 mm). Sparry calcite occupies sharp-edged intergranular spaces (5%). There are about 5% qtz. grains and clay. No fossil remains are recognizable. The calcite is in the darker, triangular zones in the picture. There are no visible shale seams or partings.

Pamelia-Lowville Transition - Sample P-B-1



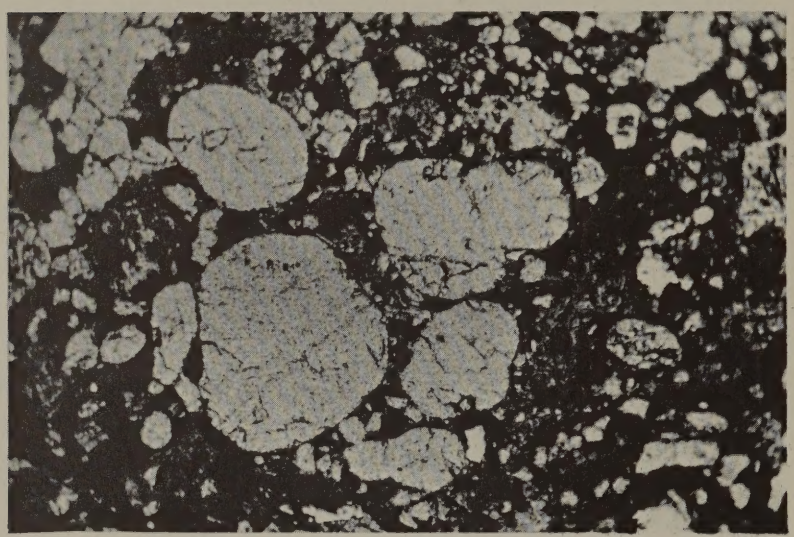
Plane Light

0.5 mm

This rock is microcrystalline, almost cryptocrystalline limestone containing approximately 15% clear sparry calcite, partly as replaced fossil fragments. The spars have an average size of 0.2 mm, but range from $<0.1$ mm to as large as 1 mm.

P-B-1 is stylolitic with grains of quartz concentrating mainly around the edges and carbonaceous material and clay within the stylolites. About 1% of the thin-section is quartz. Dolomite occurs as a few scattered grains.

Pamelia Formation - Sample P-A-1



Plane Light

0.5 mm

In this rock microcrystalline dolomite plus clay and carbonaceous material are intimately associated with the calcite and make a groundmass for subrounded grains of clastic quartz (about 30%, avg. size of 0.1 - 0.5 mm).

There are a few plagioclase and microcline feldspars, a few rhombic dolomite crystals. Sparry calcite cement occupies the intergranular spaces. 20% of the thin-section is occupied by dolomite. Some shell fragments and clay zones are present.

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